

Lagrangian and Eulerian views into a turbulent boundary layer flow using time-resolved tomographic PIV

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Abstract The momentum exchange mechanisms in a turbulent boundary layer (TBL) flow are of manifold temporal and spatial scales and governed by the organization of self-sustaining coherent flow structures driven by entrained high momentum fluid. Generic flow structures such as hairpin-like vortices and spanwise alternating wall bounded low- and high-speed streaks have been observed and extensively analyzed with both experimental and numerical methods, e.g. by means of PIV (Christensen & Adrian 2001, Kähler 2004, Stanislas et al. 2008) or DNS (Spalart 1988, Robinson 1991, Kang et al. 2007). In many studies the role of these structures for the wall normal and spanwise fluid exchange has been highlighted mostly within an Eulerian reference frame. But for a full understanding of the momentum exchange in turbulent wall flows a step towards a spatially resolved Lagrangian frame of reference would be advantageous.

The data achieved from the present application of time-resolved tomographic PIV to a flat plate turbulent boundary layer flow in a water tunnel at $Re_\theta \sim 2460$ enables for the first time a topological investigation of the flow structures and related particle motions within a temporally and spatially highly resolved Lagrangian and Eulerian reference frame.

1. INTRODUCTION

In the turbulence flow research community two branches can be distinguished which reflects the two general view points either with a more or less application driven focus on shear- and wall bounded turbulence or with a more fundamental research driven interest in s.c. homogeneous, isotropic turbulence. In the isotropic turbulence branch Lagrangian statistics on temporally highly resolved trajectories of few single spatially independent tracer particles in the flow using different PTV techniques are dominant on the experimental side, while in the shear- and wall bounded turbulence research Eulerian reference frame approaches using PIV or hot-wire probe techniques became dominant leading to concepts and models of coherent structures as the main carriers of turbulent fluid exchange. This branch development seems to be quite natural as in shear flows the intrinsic turbulent dissipation scale ε and therefore the Kolmogorov scales η and τ_η are depending on the position in space resp. wall distance for TBL, while they are universal in isotropic turbulence making assumptions on highest levels of generality possible relying on high performance DNS data (Yeung 2002, Biferale et al. 2006). However, experiments measuring turbulent flows in a Lagrangian reference frame need techniques which allow following the trajectory of (single) particles in a high temporal resolution comparable to the smallest turbulence time scales and at the same experiment also for a long observation time in order to cover also the integral time scales. Up to now the experimental Lagrangian turbulence characterization has been performed by statistical analysis over several spatially independent single or groups of particles measured by tracking methods (Virant & Dracos 1997, Mordant et al. 2007). Using these techniques the achieved spatial

resolution did not allow describing the coherent structures. One of the challenges of experimental turbulence research is therefore the combination of both viewpoints in a single experiment. Of course complete DNS and specific research topics like particle dispersion in boundary layers, two-phase flows etc. are bridging always both reference frames, but up to now no measurement technique was available which enables the possibility to capture at the same time both properties of the flow field in a high spatial and temporal resolution.

In the past two decades considerable experimental and numerical work on coherent structures in wall bounded turbulent flows has been carried out. A focus for a direct comparison of the results of the present work will be the spatio-temporal models of coherent flow structures, which have been developed partly by using the PIV techniques (e.g. Robinson 1991; Meinhart 1994; Schoppa and Hussain 1997; Tomkins et al. 2003 and Kähler 2004). Since almost two decades the PIV technique has enabled the determination of instantaneous velocity vector fields in a plane of the flow, returning important results based on instantaneous and statistical approaches to the analysis of the turbulent flow structures. Successful extensions of PIV experiments towards dual plane and/or time resolution have been performed during that time and their applications to turbulent flows emphasized the role of coherent flow structures for this research field. In a recent paper Stanislas et al. 2008 described the scaling properties, topologies and distribution functions of vortices in a turbulent boundary layer for two different Reynolds numbers at $Re_\theta = 7800$ and $Re_\theta = 15000$ by using conditional averaging and space correlation functions. They found in accordance to earlier PIV measurements by Kähler 2004 that hairpin like vortices are dominantly one sided and cane shaped, and then play a major role for the spatial organization of wall normal and spanwise flow exchange. They are apparently connected to the turbulence production events, the (instantaneous) negative Reynolds stresses $u'v'$, so called Q2- and Q4- events in the buffer and log layer. Equilibrium between production and dissipation can be assumed for the log layer. The main aim of Stanislas et al. paper is to show the possibility of a universal scaling of wall turbulence by U_e and the Kolmogorov scale η .

Diorio et al. 2007 are reporting about the results of multi hot wire measurements in a TBL. The data enables them to reconstruct the average spatial neighbourhood of dissipation and production regions. They claim to identify the highest instantaneous dissipation rates within the vortex lines of e.g. a hairpin leg, while the highest production rates are located in both spanwise vicinities as Q2 and Q4 events. In the results chapter of the present paper conditional averaging of our data at Q2 and Q4 events and the two signs of y-vorticity will return a generic 3D velocity vector topology of these neighbourhood relations (see Fig 7, 8).

A recent application of the tomographic PIV technique to a tripped turbulent boundary layer flow at a low Reynolds number has been reported by Elsinga et al. 2007. In their paper instantaneous spatial topologies of the coherent structures like hairpin vortices, packets of hairpins along low speed streaks and Q2- events have been visualized segmented in 3D quantitatively with a very high quality. The coherent structures have been extensively described and global statistics have been calculated for comparison with theory and literature. The first time preliminary results of time-resolved 3D-3C velocity vector fields from turbulent wall bounded flows in air gained by using tomographic PIV have been published by Schröder et al in 2006.

The turbulent mixing due to the Q-2- and Q-4-events, has been found to be connected to a staggered pattern of hairpin-like vortices, see idealized mixer-model of substructure formation inside a turbulent spot from Schröder and Kompenhans 2004 or in TBL from Elsinga et al. 2007. Schröder 2001 concluded an interpretation of spatial distributions of space-time correlations of the single Reynolds stress elements calculated for different planes parallel to the wall that the initial process for the formation of hairpin vortices seems to be a Q4-event which was deflected by a downstream flow structure and transformed into a Q-3 event with additional spanwise flow variance, which then interacts with a wall-near low speed streak. Such events have been found in the 3D-3C and time resolved data of Schröder et al. 2008, but could not be confirmed yet as an essential mechanism.

It will be shown that the data-set achieved by time-resolved tomographic PIV in the presented work gives valuable insight into the four-dimensional flow organization and exchange mechanisms of coherent flow structures inside a fully developed flat plate turbulent boundary layer with zero pressure gradients at $Re_\theta \sim 2460$. For the first time we can expect flow information from both reference frames: Eulerian and Lagrangian. A topological analysis by means of 3D space-(time)-correlations, PDF's of different scalars, conditional averaging and time series of instantaneous velocity vector volumes on one side and PDF's of Lagrangian accelerations and a view of particle tracks are the results presented in this paper. The Lagrangian time-scales towards integral values are of course limited by the finite extent of the measurement volume, the restrictions of the PTV algorithm in finding long paths and the overall convection velocity. On the other hand the very high time sampling rate allows to fully resolve the flow for the Kolmogorov time scales, which have been estimated from derivatives of the instantaneous u-velocity in x-directions between $\tau_\eta = 15$ to 40 ms within the measurement volume depending on the wall distance. After tomographic reconstruction of a time series of particle image recordings in volumes a PTV algorithm from *LaVision* has been employed enabling to describe the motion of several thousands of particles in a Lagrangian frame of reference within the measurement volume. This approach allows the calculation of the wall distance dependencies of the PDF's of Lagrangian accelerations and a close examination of the momentum exchange processes. Time series of instantaneous 3D velocity vector fields have been determined, while 3D-vorticity and swirling strength fields are represented by iso-surfaces, which highlight the topology of individual vortical substructures, their time development and induced flow. Swirling strength is the imaginary part of the locally calculated complex eigenvalue of the velocity gradient tensor, which is a measure for rotation excluding shear vorticity (Zhou et al. 1999). It has to be mentioned that the relatively coarse spatial grid resolution for the buffer and log-layer region in the measurement volume emphasizes the bigger vortical structures, but nevertheless the main topologies like hairpin-like vortices and low and high speed streaks have been sufficiently resolved.

2. EXPERIMENTAL SET-UP AND PROCEDURE

The experiments have been conducted in the water tunnel at TU Delft where a turbulent boundary layer flow has been established along a vertical mounted flat acrylic glass plate at a free stream velocity of 0.53 m/s. The plate dimensions are 250 x 80 cm² and an elliptic leading edge was employed, while a zero pressure gradient has been adapted by a trailing edge flap. The flow on the observation side was tripped by a spanwise attached zig-zag band 150 mm downstream of the leading edge resulting in a thickness of the turbulent boundary layer of 38 mm corresponding to $Re_\theta \sim 2460$ based on momentum thickness at the measurement volume. The temperature was controlled and hold constant, while the turbulence level of the free stream velocity was below 0.5 %. For the general characterization of the boundary layer flow a $f = 105$ mm lens from *Nikon* has been used for a high resolution 2C-PIV experiment with a low-repetition rate system composed of a Big Sky CFR-200 laser of 200 mJ pulse energy and a LaVision Imager PRO-X camera of 4 Mpixels. One thousand statistically independent double particle images in a region of $\sim 50 \times 50$ mm² have been evaluated by 8×8 pixels interrogation windows corresponding to a spatial resolution of 4.4 wall units in x- and y-direction in an ensemble correlation mode in order to calculate a high resolution boundary layer profile averaged over all wall normal columns of the gained velocity vector field. The resulting semi logarithmic boundary layer profile calculated in wall units after applying the Klauser-method for skin friction velocity estimation is given in Fig 1 (bottom-right). The skin friction velocity has been estimated by regression between $y^+ = 44$ and $y^+ = 200$ to $u_\tau = 0.0219$ m/s and the coefficient to $c_f = 0.00345$. Buffer layer, log-layer and bulk

region can be distinguished in the single wall distance regions by their characteristic curvatures, while the linear viscous sub-layer region could not be resolved sufficiently.

In a second step four cameras were applied for high resolution tomographic PIV measurements using four 4 Mpixels cameras at a rate of 1 Hz for statistical treatment of the TBL flow. The results of this investigation will be reported in another paper in future.

In a third step a high-repetition rate tomographic PIV system has been applied by making use of a diode pumped double cavity Nd:YLF high repetition rate laser from *Quantronix* with a pulse energy of 25 mJ at 1 kHz and six *Photron* CMOS cameras in 1024 x 1024 pixels full frame modus (see Fig 1 left). Five cameras have been positioned in an angular viewing geometry adapted in Scheimpflug mounts, while one camera sensor was aligned parallel to the mean flow. The volume illumination in a rectangular shape was realized by guiding the laser beam through two spherical ($f = -100$ and $f = 200$ mm) and two cylindrical lenses ($f = -90$ mm and $f = 300$ mm) and a final knife edge frame. The light was introduced parallel to the plate and perpendicular to the mean flow direction. As sufficient light was scattered by the polyamide seeding particles with 56 μm average diameter (see Fig 1 top-right) astigmatism effects could be avoided without the use of prisms by reducing the aperture of the four *Zeiss* $f = 100$ mm and two *Nikon* $f = 105$ mm camera lenses down to $f_{\#} = 11$. A volume of about $63 \times 15 \times 68 \text{ mm}^3 = 734 \times 176 \times 793 \text{ voxel}^3 = 1380 \times 328 \times 1490 \text{ wall units (WU)}^3$ in x-, y- and z direction (x- stream wise and y- wall normal) centered 2090 mm downstream of the leading edge has been illuminated at 1 kHz and 3 kHz frequency. For 5 times 2040 images were captured in a time series of 2 s at 1 kHz. Additionally one 3 kHz time series with 2040 images has been acquired. The system was synchronized with a LaVision Programmable Timing Unit (PTU9) controlled by the DaVis7.3 software. With the same software tool the reconstruction of the three-dimensional particle light intensity distributions has been calculated by means of the MART tomographic algorithm specialized for PIV signals (Elsinga et al 2006) returning a 3-D array of voxels where the intensity is digitally stored. Before final reconstruction of the particle image volumes a volume-self-calibration according to Wieneke (2007) has been performed. This procedure is necessary in order to enhance the accuracy of the iterative MART algorithm resulting in a better particle reconstruction performance and a reduction of ghost particles. The particle image volume is analyzed by local 3D cross-correlation with an iterative multi-grid volume deformation scheme reaching a final 32^3 voxels interrogation box size. For particle image cross-correlation the Δt between two reconstructed volumes has been chosen to be 2 ms in order to enhance the dynamic range of the velocity fluctuations and reduce the number of correlated ghost particles (when evaluating all samples 50 % overlap in time). The presence of ghost particles is a statistical result of the MART algorithm and for a given seeding density (here about 0.05 ppp) their probability of appearance decreases with the number of cameras viewing from different angles. They become uncorrelated for larger time steps in between two frames. With a given magnification of 85.9 $\mu\text{m}/\text{voxel}$ the final 32^3 voxels corresponds to a spatial resolution of $\sim 2.75 \times 2.75 \times 2.75 \text{ mm}^3$ and with 75 % overlap a series of instantaneous three-dimensional velocity vector volumes over a grid of $92 \times 99 \times 22$ (200,376) measurement points located every 0.687 mm ~ 15 WU in all directions in space for each time step of 2 ms increment have been achieved.

In a fourth time resolved tomographic PIV set-up the bulk region and outer layer of the TBL has been under investigation in order to capture the intermittency rates and entrainment events of high momentum fluid. This part of the experiment will also be reported in another future publication.

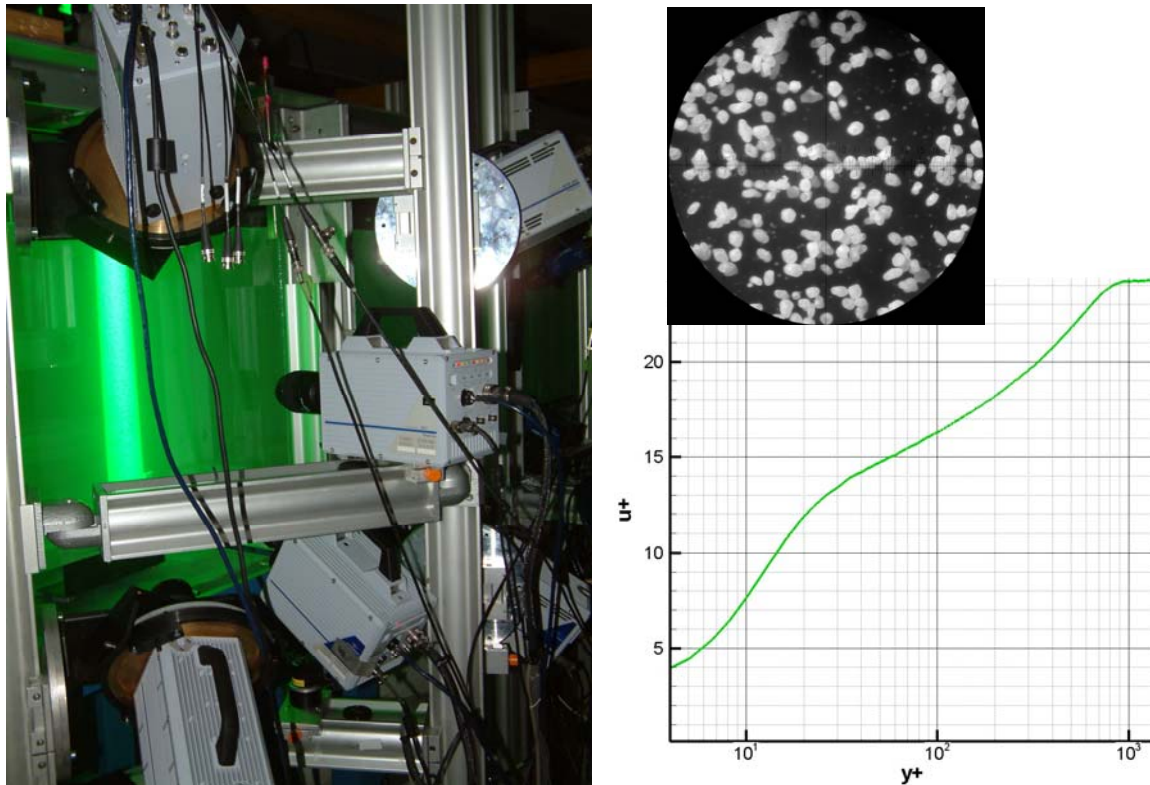


Fig. 1. Six CMOS cameras at 1 kHz framing rate in featuring a solid angle view at TU Delft water tunnel. The measurement volume of $63 \times 15 \times 68 \text{ mm}^3$ was located in a turbulent flat plate boundary layer flow 2.09 m downstream of the leading edge (left). Polyamide seeding particles with $\sim 56 \mu\text{m}$ mean diameter (top-right). Profile of turbulent boundary layer at $Re_\theta \sim 2460$ at measurement position (bottom-right).

3.RESULTS

3.1 Instantaneous 3D-3C(t) velocity vector fields

Processing of 10200 tomographic particle volume reconstructions by MART and local 3D cross-correlations of 5100 (each second pair) has been realized on two four times dual-core 64 bit clusters within two month of computing time by using DaVis 7.3. Instantaneous velocity vector volumes with a mean particle image shift of ~ 9 voxels were calculated and after conversion to physical quantities 3D vorticity and swirl strength have been determined besides the overall average over all 5100 samples. After subtracting the mean from the single instantaneous velocity vector volumes the fields of fluctuation velocities u' , v' and w' and the four quadrants of the Reynolds stress Q1 to Q4 have been derived. Examples of the results of global and local statistics are shown in the next chapters.

The 4D data with more than 200000 instantaneous velocity vectors for each volume measured with 1 kHz provide all important information about the flow structure development and spatio-temporal distribution of many significant flow events in this low Reynolds number TBL. Such data-set was desired often in former investigations of wall bounded turbulent flows. The number of spurious vectors was less than 1 %. For the single instantaneous velocity vector plots an uncertainty of about ~ 2 % has to be accepted, because a sub-pixel accuracy of the peak detection of ~ 0.15 pixels was always present.

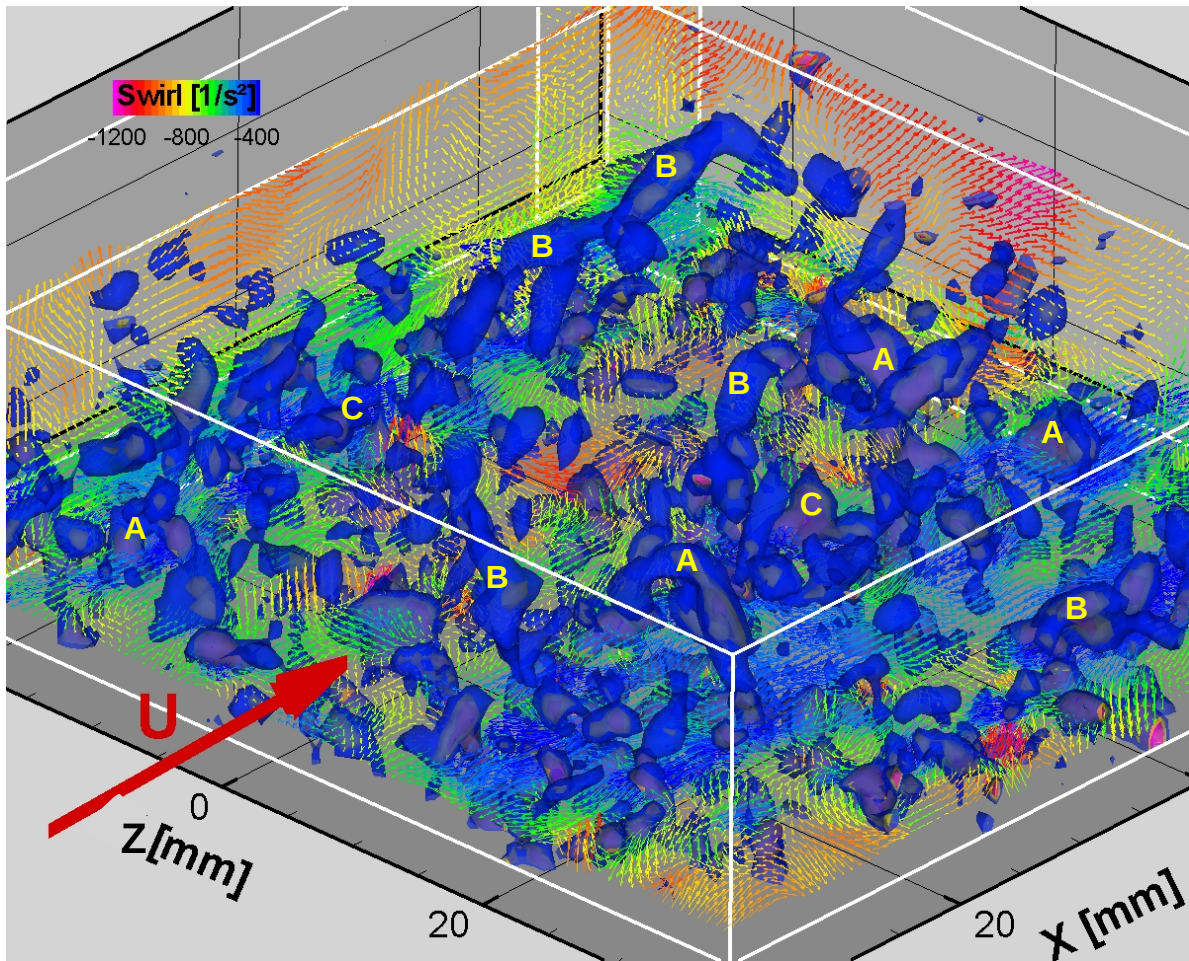


Fig. 2. An instantaneous 3D-velocity volume extracted from a time series depicting flow structures by iso-surfaces of swirl-strength and selected velocity planes at $y^+ \sim 75$ ($u - u_{ref}$ color coded, $U = 0.53$ m/s)

In Fig 2 a snapshot out of the time series of velocity vector volumes shows the distribution of vortical structures formed as arch or hairpin-like (A), cane (B) or arbitrary (C) vortices within the turbulent flow visualized by the iso-surfaces of the swirl-strength. The colour coding of the vectors represents the $u - u_{ref}$ velocities indicating low and high speed regions. It is visible that low speed streaks are closely surrounded by vortical structures of different scales, while the smaller ones (mostly not sufficiently resolved) are close to the wall, confirming the assumptions of former investigations (e.g Kähler 2004) that the near-wall streak structures are the most important shear- and -in a basic Kelvin-Helmholtz instability type - also vorticity generating structures in wall bounded flows. Nevertheless, most of these vortical structures remain stable over longer times while convecting downstream. They are slightly increasing in height while canes induce sometimes a “counter rotating vortex leg” on the opposite side of a low speed streak, but often on a slightly different streamwise position. New arch or cane shaped vortices are observed to be created seldom and are located laterally to low speed streaks, while if so, a shift and meandering of the streaks is mostly connected to strong single-sided hairpins or cane vortices in our data set. In some cases very low speed streaks are formed by or connected to packages of successive arch vortices as described in Christensen and Adrian 2001 and Ganapathisubramani et al. 2003. The extensive phenomenological study on the time evolution of the flow structures visualized by quantitative volumetric vector- and iso-surface data can give a feeling for the huge variety of flow structures present in the flow, which are not being “famous” and detected by guided perception. A topological

analysis by space-time-correlations and conditional averaging is still necessary for a more general analysis of the coherent flow structures.

3.2 PDF's and space-time-correlations

For a global statistic view the PDF's of the velocity and vorticity components can give a quick overview of the fluctuations present in the TBL flow. Skewness and shoulders visible at the PDF of u , v and w calculated over 3400 samples of the entire measurement volume shown in Fig 3 indicate how the velocity fluctuations are distributed especially in the low- and high- speed streaks as the most important non-isotropic structure in TBL. There are higher negative u' values visible in the PDF due to the spanwise spatially confined but more intense low speed streaks. Around 0.35 m/s additionally a distinct shoulder can be observed representing the average low speed streak, but the highest values are seldom. Low positive u' are more often as low negative ones as the broader high speed streaks are less intense. There is a connection between streaks and the presence of negative and positive v' , but the v distribution function depends strongly on the wall distance. The PDF of the w component is almost symmetric as it should be without spanwise pressure gradients. The PDF of the instantaneous Reynolds stresses $u'v'$ shows the characteristic skewness towards the turbulence production terms: the negative $u'v'$ consisting of Q2 and Q4 events.

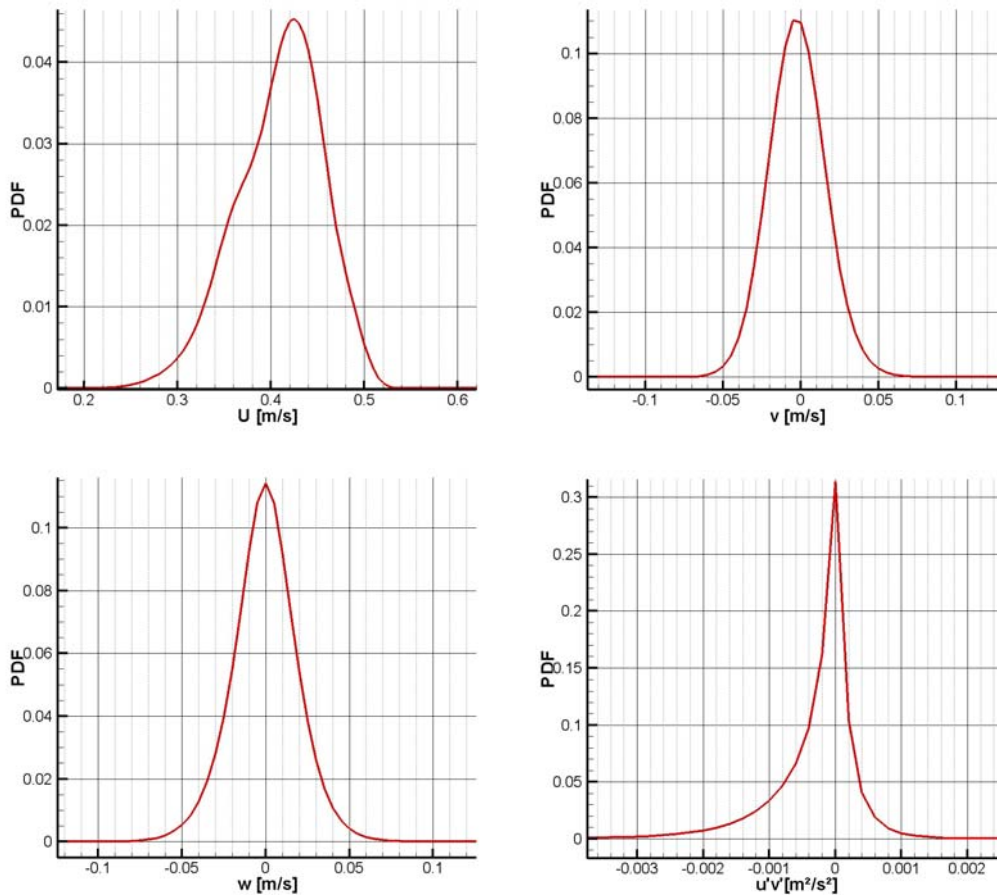


Fig 3. PDF with band width of 0.01 m/s for u (left-top), v (right-top), w (left-bottom) and $u'v'$ (right-bottom) calculated for the entire measurement volume over 3400 samples

A way to produce a more general analysis of coherent structures is the calculation of the 3D-space-time- correlation functions for the three velocity fluctuations u' , v' and w' or u'_{ij} (Eqn [1]), which provide additionally statistical information on the micro- and macro scales.

$$R_{ij}(\Delta x, \Delta y, \Delta z, \Delta t) = \frac{\sum_x \sum_y \sum_z \sum_t u_i'(x, y, z, t) * u_j'(x + \Delta x, y + \Delta y, z + \Delta z, t + \Delta t)}{\sqrt{\sum_x \sum_y \sum_z \sum_t u_i'^2(x, y, z, t) * \sum_x \sum_y \sum_z \sum_t u_j'^2(x + \Delta x, y + \Delta y, z + \Delta z, t + \Delta t)}} \quad [1]$$

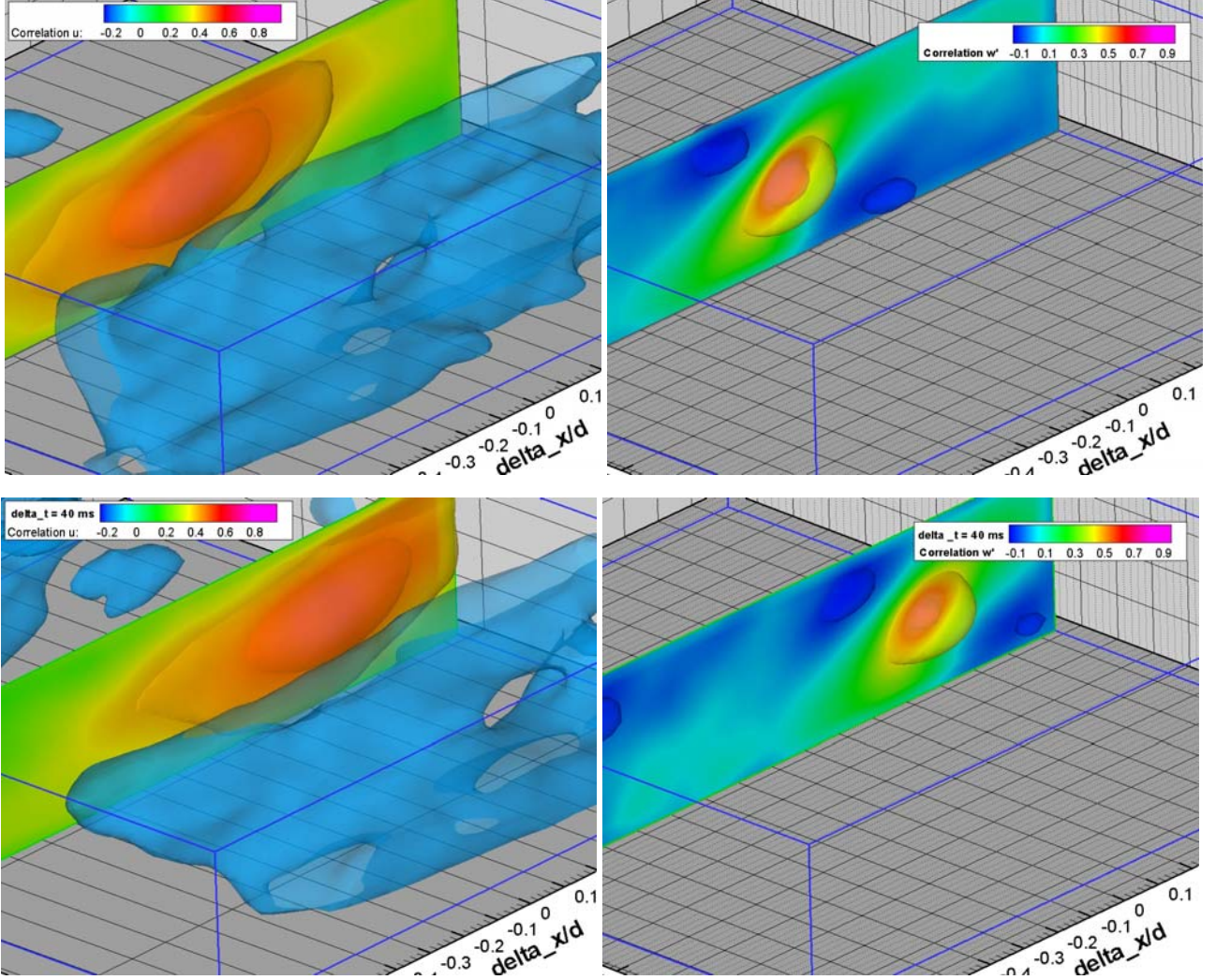


Fig. 4. 3D space-time-correlation functions for u' with negative correlation maxima visible at $\Delta z \sim 0.5\delta$ or $\Delta z^+ = 415$ in spanwise directions (left) and w' (right) at $y = 7.45$ mm or $y^+ = 163$ of the turbulent boundary layer flow for $\Delta t = 0$ ms (top) and $\Delta t = 40$ ms (bottom).

In Fig. 4 the result of 3D two-point space-time-correlation functions for u' and w' is shown for two different time steps at $t = 0$ ms and $t = 40$ ms at $y^+ = 163$ in wall normal position. A nearly non-directional form of the correlation function has been determined for the wall normal fluctuation velocity v' (not shown here). The correlation function is visualized by iso-surfaces of the correlation coefficient in the normalized range $R_{ij} = [-1; 1]$. Due to the strong time dependence of the velocity vector volumes (one aim was to achieve Lagrangian statistics) the average has not been smoothly converged over the 5100 samples, especially visible at the shape of the lower correlation coefficients. However, for u' one can see the form of the positive correlation area which is stretched in streamwise directions and negative correlation regions at $\Delta z \sim 0.5\delta$ according to the streaky formation in the flow. The coherence in time is quite remarkable for both u' and w' as after $t = 40$ ms the structure has been convected almost $\Delta x/\delta = 0.42$ downstream (Fig 4). The measurement volume in streamwise directions is $x^+ = 1380$ WU or $1,66 \delta$, so that the correlation domain is

slightly limited in x - directions according to the literature assuming x^+ values for the streamwise integral length scale for u' close to the wall up to 1500. The positive part of the correlation function is pointing downwards to the wall in upstream direction and upwards in downstream direction indicating that at the downstream tip of such streaks there is either lower momentum over higher momentum fluid for low speed streaks or vice versa for the tip of high speed streaks. This phenomenon can be explained by the formation history of hairpin-like vortices along the low speed streak, where at the downstream end separated heads convect further downstream at higher wall distances. For high speed streaks this characteristic could be caused by the blockage of a downstream located near wall flow, where the high momentum fluid can only move upwards or sideways. A separated space correlation for achieving the phase relation of positive and negative u' and v' in a turbulent spot reported in Schröder 2001 showed that if there is a negative u' then the probability for a positive v' is equal in down- and upstream directions (along a low speed streak), but if there is a positive u' then a negative v' is only of high probability upstream of that event. This is confirmed by the results of the conditional averaging in the present data shown in the next chapter. For the space-time-correlation function of the w' component (Fig 4 right) an interesting three dimensional feature can be detected. For any spanwise velocity fluctuation present an inclined positive correlation at approximately 45° to the wall can be seen, while two negative correlation regions indicating opposite spanwise flow are present perpendicular to the inclined axis, one close to the wall in downstream- and one further away from the wall in upstream direction. This is only explainable by inclined cane or hairpin-like vortices. But the most interesting part is visible in the w' space-time-correlation at $t = 40$ ms (Fig 4 right-bottom) where an upstream following structure of almost the same spatial distribution of positive and negative correlation coefficients is visible. This is a further confirmation of the upstream effect or follow-up creation of hairpin-like vortices which is quite probable along a low speed streak and was often reported in literature.

3.3 Conditional averaging

For the vortices and their connection to the turbulence production, namely the Q2 and Q4 events a conditional averaging has been employed over the whole dataset. Therefore a detection and segmentation algorithm has been developed that searches first for values above a certain threshold and secondly requires a certain number of neighbors within the area above that threshold. Then a 3D box with all instantaneous velocity vectors around that event detected with a distinct wall distance (here $y = 6.87$ mm corresp. to $y^+ = 150$) has been cut out of the single instantaneous velocity vector volume. All boxes around all found events in 5100 samples have been averaged for gaining a smooth generic topology around the chosen event. Results of the averaged 3D vortex structure for the positive and negative y -vorticity component events with the thresholds ± 0.05 1/s and the related Q2 and Q4 flow through a horizontal plane is shown in Fig. 5. One can see the vortex structures, connected to both y -vorticity signs, are inclined by an angle of approximately 45° . The values for Q2 events are ~ 2 times higher, but with limited spatial extension, compared to Q4 events. Both production events are located directly in the spanwise vicinity of the vortex tube depending on rotation direction. A weak second vortex structure of a different form with an opposite sign, but only ~ 15 % vorticity can be found on the opposite side of the low speed and Q2 event, indicating the low probability of the appearance of *symmetric* hairpin-like or arch vortices along low speed streaks, while streamwise shifts of the counter vortex is an additional reason for this low vorticity value.

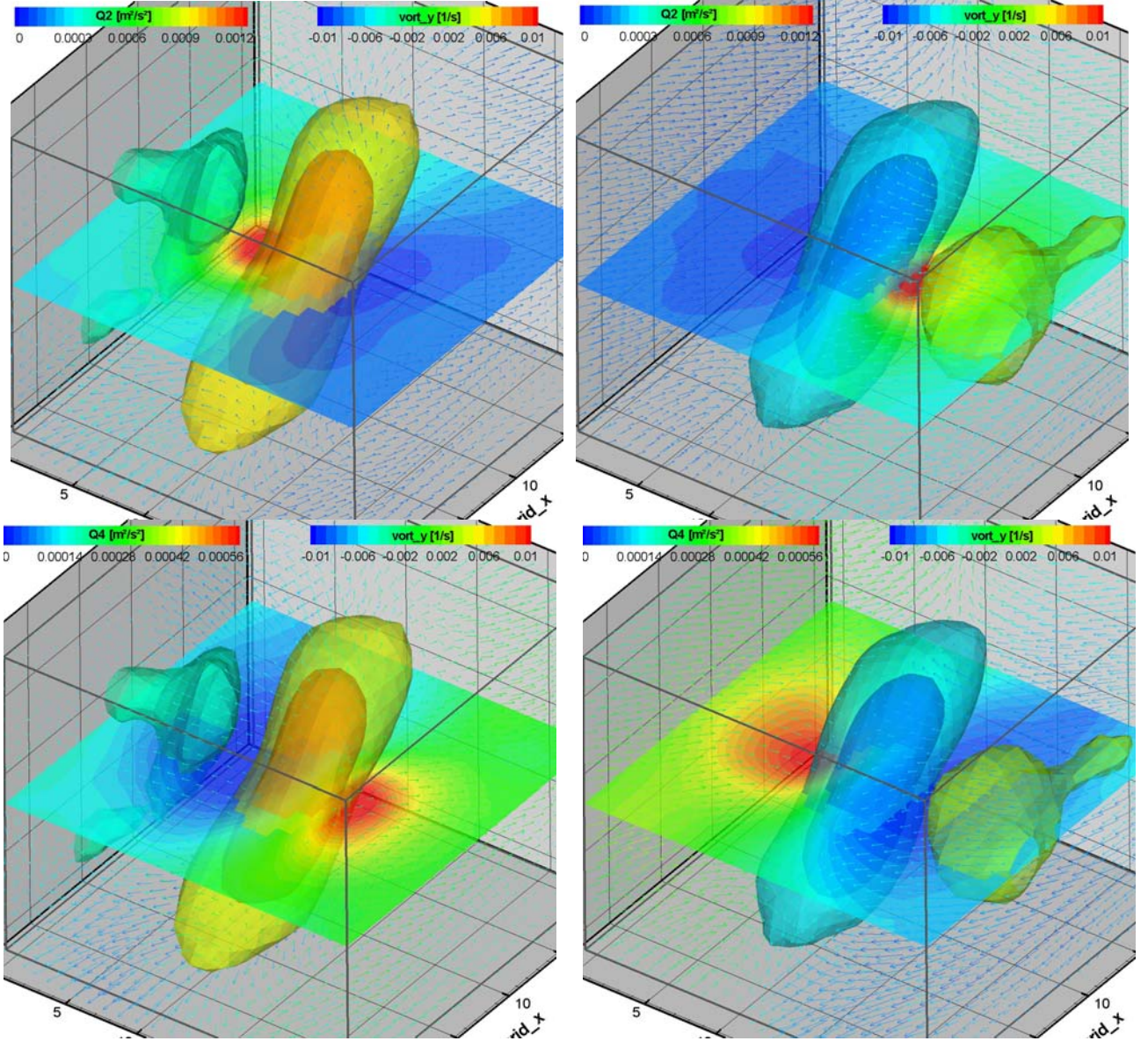


Fig. 5. Generic 3D topology of conditional averaged y-vorticity separated by sign (plus-left and minus-right) represented by iso-surfaces and corresponding Q2- (top) and Q4- (bottom) events represented by the contour plot with magnitude color coding in a horizontal plane at $y^+ = 150$

For the strong Q2- (threshold $0.004 \text{ m}^2/\text{s}^2$) and Q4- (threshold $0.0025 \text{ m}^2/\text{s}^2$) events a conditional averaging has been performed with the same technique. One can see in Fig. 6 that both strong events are laterally accompanied by a pair of counter rotating vortices, which are shaped only slightly like hairpin-legs. This confirms the dominant role of vortices for the turbulence production in general, and of hairpin-like vortices specifically. The symmetric definition of the Q2- and Q4 events leads to this symmetric appearance of vortices. For the Q2 case the distance of the averaged vortex cores is $\Delta z^+ = 120$ and for the Q4 case $\Delta z^+ = 140$, which supports the spanwise spacing found in literature (e.g. Stanislas et al 2008). The distances are reflecting the medium spanwise size of strong Q2- and Q4- events and are not in correspondence to the medium distance of $\Delta z^+ = 415$ found between positive and negative u' -streaks in the space-correlation function shown in Fig 4, but the larger value can be a result of the weaker correlation convergence. Within the restrictions of using thresholds the average strong Q4 events are about 70% of the intensity of the average strong Q2 events. Thresholds are always a selection mechanism, but even relative thresholds are not easier to be justified. However, an overlaying low speed region can be found downstream of the Q2 event

and symmetrically an overlaying high speed region is located upstream of a Q4 event. The spanwise exchange is guided only by the two vortices.

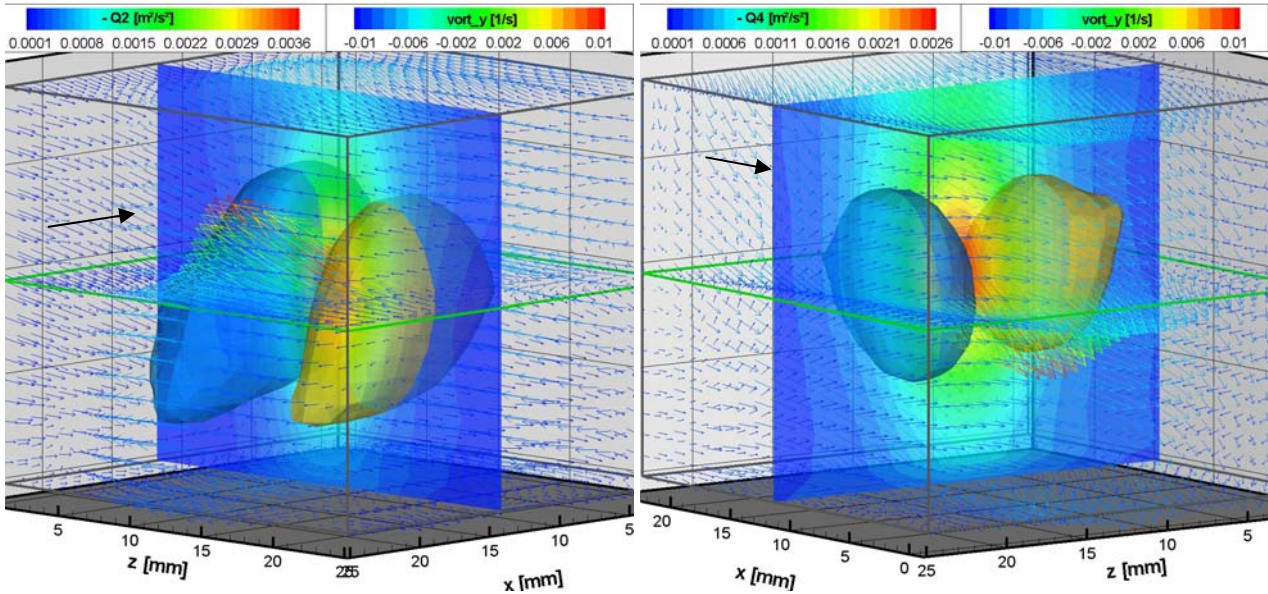


Fig. 6. Conditional averaged 3D- velocity vector volumes over Q2 events (left) and Q4 events (right) at $y^+ = 150$ and lateral located y- vorticity iso-surfaces, color coded by sign and strength

3.4 Lagrangian views and statistics

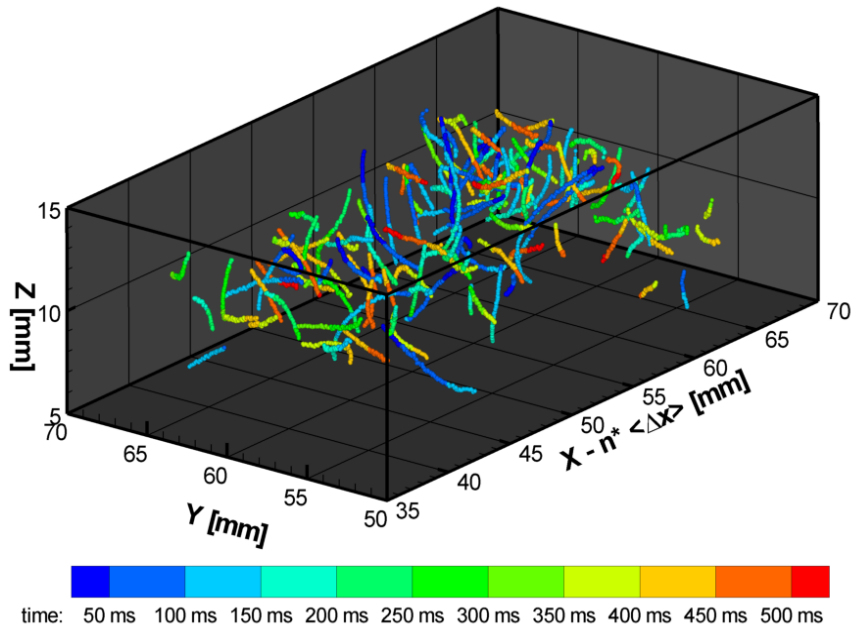


Fig. 7 Selected 3-D Particle trajectories in a section of the investigated volume. Color coded time scale starting with the beginning of the measurement. For convenience, the displacement difference to the mean velocity is displayed in case of the X component.

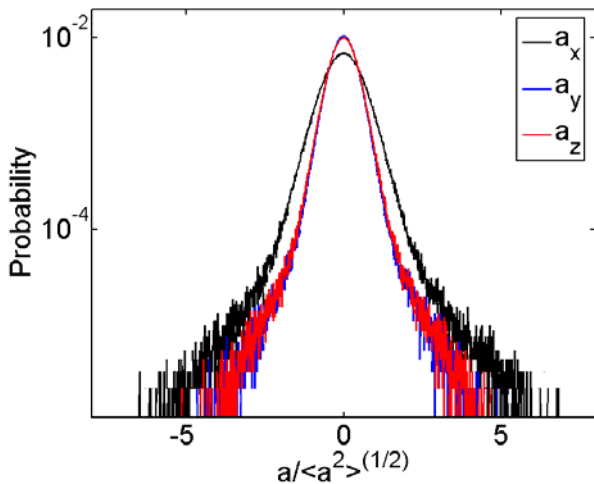


Fig. 8: Acceleration distribution. PDFs of the accelerations normalized by their standard deviations.

tracks longer than 10 time steps are taken. Ambiguities arising when a particle could possibly be connected to several particles at the next time step or multiple particles be connected to the same next particle are resolved by taking the path where the particle intensity remains the most similar. Figure 7 shows selected 3-D Particle trajectories in a section of the investigated volume. Note that the figure depicts only a small fraction of the overall identified trajectories. The total number of tracked particles is in the order of 10^5 . In order to calculate the Lagrangian accelerations, a moving cubic spline is used. For each time step, t , and around each point of a measured trajectory a third order polynomial is fitted from $t-5 \Delta t$ to $t+5 \Delta t$ for each component, x, y, z . This results in a fit to 11 measured trajectory points. The acceleration is then derived from the second derivative of the polynomial at the respective time step (see Lüthi 2002 for more details). Figure 8 depicts the PDFs of the accelerations normalized by their standard deviations. A detailed interpretation of the Lagrangian acceleration goes beyond the scope of this paper. But as a first result, it can be seen that the acceleration distribution has a more intermittent character then described by a Gaussian distribution.

4. CONCLUSIONS

The tomographic PIV technique has been applied to time-resolved particle images for an investigation of the coherent structures in a turbulent boundary layer flow along a flat plate in a water tunnel at $Re_\theta \sim 2460$. Six high speed CMOS cameras are imaging tracer particles which are illuminated by two high repetitive pulse lasers in a volume of $1.668 \times 0.398 \times 1.798$ at 1 kHz. Each of two subsequently acquired and reconstructed particle distributions have been cross-correlated in small interrogation volumes using iterative multi-grid schemes with volume-deformation in order to determine a time series of instantaneous 3D-3C velocity vector fields.

The measured series of 4D instantaneous velocity vector volumes give valuable insight into the complete flow topologies within the TBL. Consistent and frequently appearing flow structures can be identified and related to the known models (arch- or hairpin- vortices, streaks etc.). Furthermore the results of this experiment provide valuable data for the validation of numerical codes. Conditional averaging over certain flow events found inside the 3D velocity volumes provides a model of the connection of the turbulence producing Q2- and Q4-events and vortices in a spatial flow topology. Furthermore the measurement method offers the possibility to determine the

For the detection of tracer particles in the time series of reconstructed particle image volumes a 3D-PTV algorithm from LaVision has been employed. Sub-pixel 3D-particle locations are fitted within the volume by a $5 \times 5 \times 5$ Gaussian fit for all peaks above a certain threshold. Possible particle matches are restricted by several criteria.

First velocities must fall within a global possible range, and the change in velocity from one time step to the next must be below an absolute value (here 1 pixel) and also less than an allowed velocity gradient in pixel-displacement / pixel-distance (here 0.5).

Finally particles must be visible for several time steps. Given the high density of reconstructed particles with the presence of a high fraction of ghost particles only particle

complete time dependent three-dimensional velocity gradient- tensor within the measurement volume. The fluctuation components, vorticity, Reynolds stress events and the elements of the velocity gradient tensor can be time-space-correlated in the whole volume. Additionally the PDF's of Lagrangian accelerations have been calculated as a first result within the moving reference frame. Lagrangian time-correlations and particle trajectories in combination with the Eulerian 4D fields and various scale analysis in further future post-processing steps of the present data set will prospectively be published in a more extensive paper in future. The aim is to contribute to an enhancement of the understanding of structural self-organization processes, scaling properties and the energy and momentum budgets of wall bounded turbulent flows in the near future.

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