APPLICATIONS OF MULTI-PULSE SHAKE-THE-BOX 3D LAGRANGIAN PARTICLE TRACKING TO SINGLE- AND MULTI-EXPOSED RECORDINGS

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ABSTRACT: *Lagrangian particle tracking (LPT) enables the accurate measurement of position, velocity and acceleration of single seeding tracers imaged by a multiple camera system. The Shake-The-Box (STB) technique extended the capabilities of 3D particle tracking methods to higher seeding densities, thus providing access to the full velocity gradient tensor. The STB method, initially proposed for the reconstruction of time-resolved sequences of recordings, has been extended to the case of short recording sequences acquired by multi-pulse systems for the investigation of high-speed flows. The Multi-Pulse Shake-The-Box technique (MP-STB) exploits an iterative strategy to make up for the lack of time-resolved recordings and progressively simplify the reconstruction and tracking problem, therefore increasing the number of successfully identified particle tracks. Individual track fields from MP-STB can be exploited to describe the instantaneous flow structures by means of interpolation to a regular grid or collected into bins with an ensemble-average approach to produce highly spatially resolved statistics. Several applications of the MP-STB technique to turbulent boundary layer flows and to a high speed free jet in air are presented here. The experimental conditions are described together with the main processing parameters adopted for the iterative STB strategy. The multi-pulse recording sequences are obtained by means of two pulse separation techniques (polarization- and timing-based) and by adopting Multi-Exposed recordings. Results are shown in terms of instantaneous fields and flow statistics.*

1 Introduction

The Shake-The-Box technique (STB [12]) is a processing algorithm for the 3D reconstruction of individual tracks from particle images acquired in a time-resolved fashion from a multi-camera imaging system. The STB method is based on the Iterative Particle Reconstruction (IPR [17]); an initial phase where tracks are identified over the first few realizations is followed by the prediction of the particle location at subsequent recordings. The predicted location is then corrected by means of an image matching scheme (shaking step). The method relies on the availability of a time-resolved sequence of recordings to be able to accurately reconstruct a large number of tracks (exceeding 0.1 particles per pixel - ppp) nearly free of ghost particles [3]. The scattered information obtained from Lagrangian particle tracking can be accurately interpolated onto a regular grid by means of cubic b-splines (FlowFit [5]) allowing for the evaluation of spatial gradients and, given the accurate material acceleration measurement provided by particle tracks, of instantaneous 3D pressure fields [16][15].
Due to the current limitations in terms of acquisition frequency of high-speed systems, when dealing with higher flow speeds relevant for aerodynamics and industrial applications (typically larger than $50\ m/s$) time-resolved sequences of recordings are not available. In this situations multi-pulse systems

can be employed which make use of dual acquisition and imaging systems synchronized in a staggered fashion to produce short sequences of (typically four) time-resolved recordings [14][6][1].
The Multi-Pulse Shake-The-Box (MP-STB) technique has been recently proposed by [10]; the lack of time information provided by time-resolved recordings is compensated for by the adoption of an iterative strategy for the reconstruction and tracking process. After each iteration, successfully identified four-pulse tracks are subtracted from the original recordings thus reducing the perceived seeding density of the images used for the following reconstruction and tracking iteration. As a consequence, the complexity of the reconstruction and tracking problem is progressively reduced and the number of reconstructed tracks increased. The performances of this novel strategy have been demonstrated by means of synthetic experiments and the technique has been successfully applied to the investigation of several flows in air in a wide range of velocities. The main strategies for the acquisition and processing of Multi-Pulse STB recordings are described in section 2, while several experimental investigations performed with MP-STB are presented in section 3.

2 Shake-The-Box for multi-pulse sequences

Multi-pulse sequences consist of typically four recordings acquired within rapid succession in order to guarantee a relatively small particle displacement (around $15 \div 20$ pixels) between subsequent exposures. Two double-pulse lasers are employed to generate four pulses; the time separation between the pulses can be freely chosen (down to a few microseconds) adjusting the staggered emission of the two illumination systems.
A number of double shutter PIV cameras, arranged in a 3D imaging system, is typically employed to record the light scattered by the particle tracers at each pulse. Due to the read-out time of the first frame, the second exposure time is typically very long (several milliseconds) when compared to the time-separation between the pulses; as a consequence, different approaches can be adopted to separate the pulses onto the camera frames. Alternatively, multi-exposed images can be used, where the same particle is imaged at several times within the same camera frame.
Three different strategies for the recording of multi-pulse sequences are described in section 2.1, and adopted for the experimental investigations shown in section 3.
Depending on the chosen pulse generation and recording approach, the Multi-Pulse STB processing strategy requires being adapted concerning mainly the tracking step; nevertheless, the iterative approach described in section 2.2 can be adopted independently of the chosen recording technique.

2.1 Acquisition strategies for multi-pulse recordings

The performances of particle reconstruction techniques in terms of reconstruction accuracy decrease at higher seeding density; the Iterative Particle Reconstruction technique employed within the STB algorithm is typically limited to approximately 0.05 particles per pixels (ppp). As a consequence, single exposed particle images represent the preferred choice when high instantaneous spatial resolution is required (e.g. for the evaluation of instantaneous spatial gradients).
In this case, two 3D imaging systems are employed in order to separate the four pulse emitted by the dual illumination system on the camera frames. Within the development of MP-STB, two approaches have been investigated [8], where the pulse separation is implemented by means of a *polarization-based* technique or via a *timing-based* approach.
The first technique relies on the use of polarized light, where two double cavity lasers emit at orthogonal polarization directions and camera lenses are equipped with polarization filters to separate the pulses on the different camera frames (following [14]). As the scattered light from the particle

needs to retain the polarization direction, this approach is limited to spherical tracers. For the same reason, the maximum angle between the cameras viewing direction and scattering plane is limited to approximately 20^o. The acquisition scheme followed when adopting the polarization-based approach is shown in Figure 1.

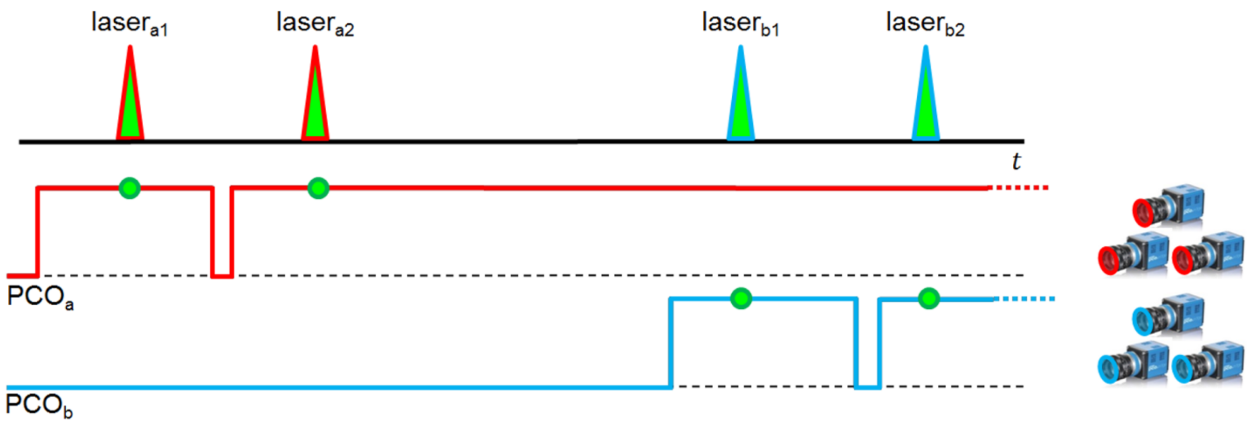

Figure 1. Pulse separation timing diagram for the polarization-based strategy; red and blue colors indicate the horizontal and vertical polarization directions respectively, *a* and *b* refer to the two illumination and imaging systems, 1 and 2 to the first and second laser pulses.

The timing-based approach makes use of framing optimized cameras (FOX [4]) capable of acquiring two frames with short exposure time at the expense of halving the sensor resolution along one direction; this strategy is depicted in Figure 2.

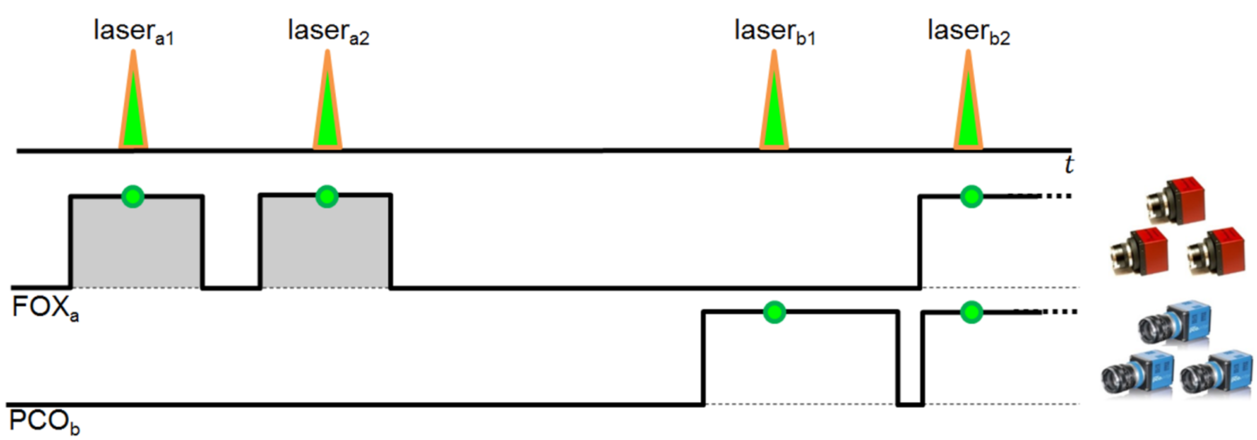

Figure 2. Pulse separation timing diagram for the timing-based strategy; orange indicates circular polarization. Gray areas indicate the FOX frames at reduced resolution.

Both the aforementioned techniques require the use of two imaging systems, each consisting of typically three or four cameras imaging the same illuminated volume. Due to restrictions in terms of availability of cameras and/or optical access to the test section (particularly limited in many industrial applications), the use of a large number of cameras is not always possible.

In order to ease on this limitation and to simplify the experimental setup, a strategy based on the use of double-exposed recordings can be implemented, where the first two pulses are recorded on the first frame and the last two on the second frame, Figure 3. With respect to the approaches previously presented, the effective seeding density is limited, but only one 3D imaging system is required.

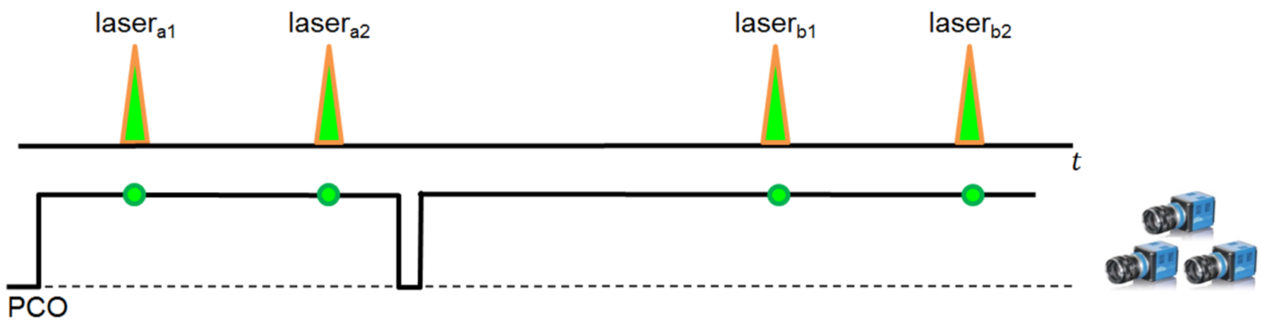

Figure 3. Timing diagram for the multi-exposed acquisition strategy.

2.2 Iterative MP-STB processing strategy

Independently of the chosen approach for the acquisition of the multi-pulse recordings, the iterative approach shown in Figure 4 is followed for the data processing.

The recorded images are reconstructed by means of IPR to obtain the particles location and intensity within the investigated volume. Subsequently single particles are tracked over the four exposures; the tracking technique is adapted depending on the chosen pulse generation strategy. Details about the particle tracking algorithm can be found in [10][9].

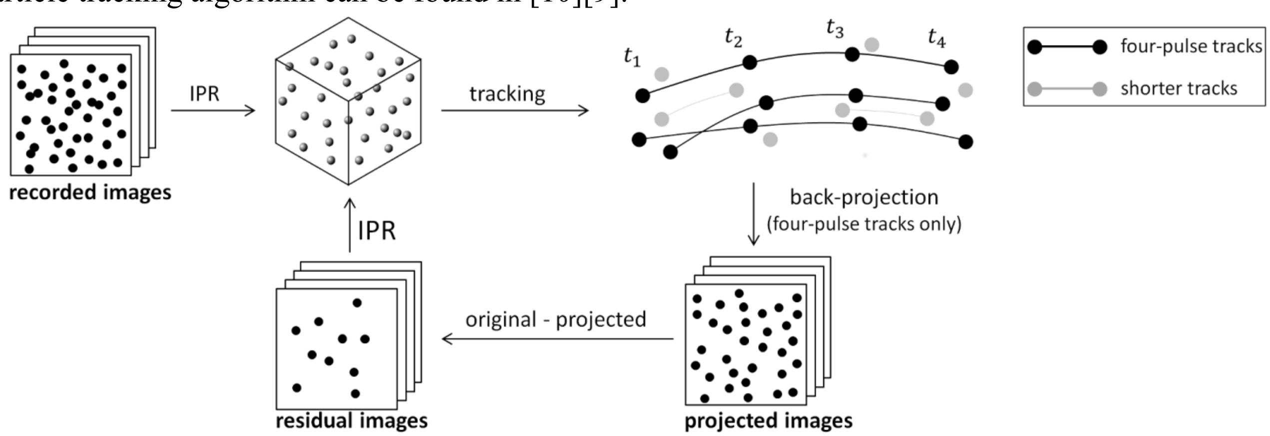

Figure 4. Iterative processing strategy for MP-STB. The IPR reconstruction of recorded/residual images, the tracking step and the evaluation of back-projected and residual images constitute a single STB iteration.

Particles that can be tracked over the complete sequence have a higher chance of being actual particle tracers and not spurious intensity peaks resulting from the underdetermined nature of the reconstruction process (see [3][2]). Therefore, after the tracking step, only the particles that could be tracked over the four pulses are retained and back-projected onto the camera image planes; subtracting these projected images from the original recordings yields the residual images that are fed into the reconstruction and tracking algorithm for the following MP-STB iteration.

The lower imaged seeding density of the residual images represents an easier problem for the reconstruction and tracking steps allowing for the identification of new particle tracks at subsequent iterations. Typically 3 ÷ 5 iterations are employed for the analysis of experimental data.

3 Experimental applications of Multi-Pulse STB

In this section several experimental applications of Lagrangian particle tracking by means of Multi-Pulse Shake-The-Box are presented. Four-pulse recordings sequences have been generated adopting one of the strategies shown in section 2.1; the experimental setups and main processing parameters are described and results in terms of instantaneous velocity fields and flow statistics are presented

3.1 Turbulent boundary layer in adverse pressure gradient

The experiment is conducted in the large scale Atmospheric Wind tunnel Munich (AWM) at the Bundeswehr University (Munich, Germany). The closed test section of the open circuit facility is 22 m long and has a cross-sectional area of $1.8 \times 1.8\, m^2$. The free stream velocity in the test section is 36 m/s. The model shown in the sketch in Figure 5 is located at the vertical wall of the test section in order to produce an adverse pressure gradient within the turbulent boundary layer; the model is approximately 7 m long and encompasses the whole height of the test section. A multi-planar large-scale PIV system consisting of nine sCMOS PIV cameras is placed on top of the test section to measure the whole extension of the boundary layer over approximately 2.3 m in stream-wise direction (X axis). A long-range micro-PIV system is used to investigate the near-wall region located within the same measurement domain of the tomographic system. Details about the 2D-PIV and long-range micro-PIV measurements can be found in [11].

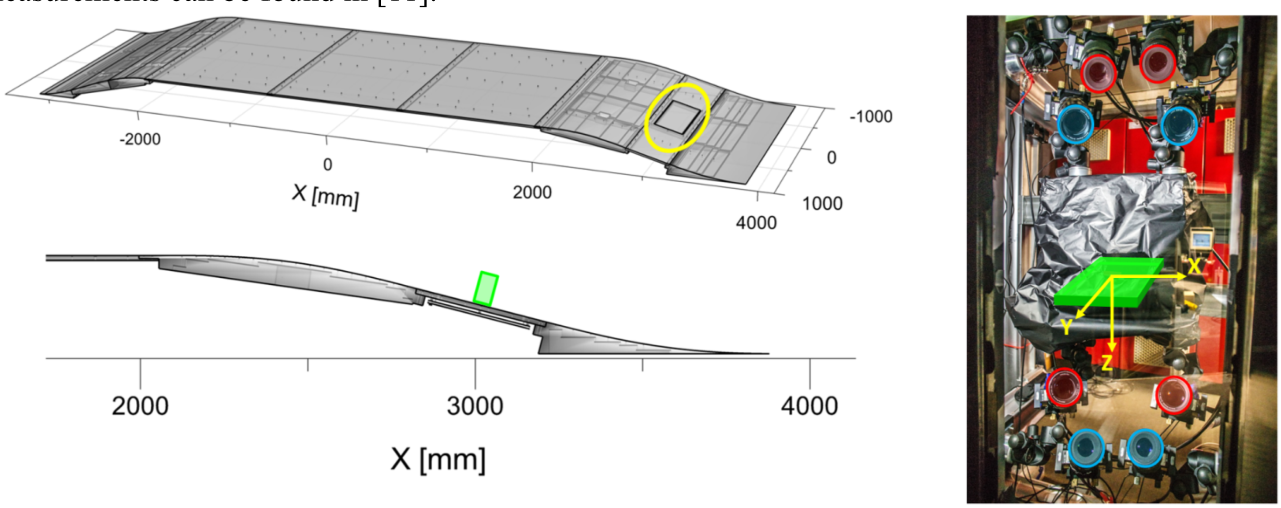

Figure 5. Two views of the wind-tunnel model; yellow circle indicates the location of the glass window used as optical access for the imaging system, the MP-STB investigated volume is indicated in green. The two imaging systems (four cameras each) are indicated with blue and red circles according to the polarization direction of the laser light (vertical and horizontal).

The 3D measurement domain extends for 90 mm normal to the glass wall (Y direction) and encompasses 50 mm along the stream-wise direction; the thickness of the illuminated area extends for approximately 8 mm along the span-wise Z axis. The two imaging systems consist of four PCO.Edge cameras each (sensor size: $2560 \times 2160\, px$; pixel size: 6.5 μm); the digital resolution is approximately 35 px/mm. Illumination is provided by two double-cavity BigSky CFR 400 lasers emitting at two orthogonal polarization states and combined onto the same optical axis.
The flow is seeded with DEHS (Di-Ethyl-Hexyl-Sebacate) droplets (diameter: 1 μm); the imaged seeding density is approximately 0.04 ppp.

multi-pulse sequences of four pulses are generated with a constant temporal spacing of $10\ \mu s$; the four pulses are recorded by the two imaging systems following the polarization-based strategy shown in Figure 1. With the chosen time separation the maximum particle displacement between subsequent pulses is approximately $15\ px$. A sequence of $20{,}000$ recordings is recorded with a frequency of $10\ Hz$; for each recording, a four-pulse time-resolved sequence is available.
The iterative processing technique shown in Figure 4 is applied; five MP-STB iterations are employed, leading to the identification of approximately $90{,}000$ individual instantaneous tracks. A more detailed description of the reconstruction and tracking processing parameters can be found in [10].
The particle locations along the four pulses are fitted by means of a second order polynomial and the tracks position and velocity are obtained from the polynomial fit; an instantaneous MP-STB result is presented in Figure 6, where the tracked particle locations are shown by means of a spherical marker color-coded by the stream-wise velocity component. The scattered information provided by the particle tracking approach is then interpolated onto a regular grid by means of a system of cubic b-splines (FlowFit method [5]), which allows for the evaluation of spatial gradients (Figure 6-rigth).

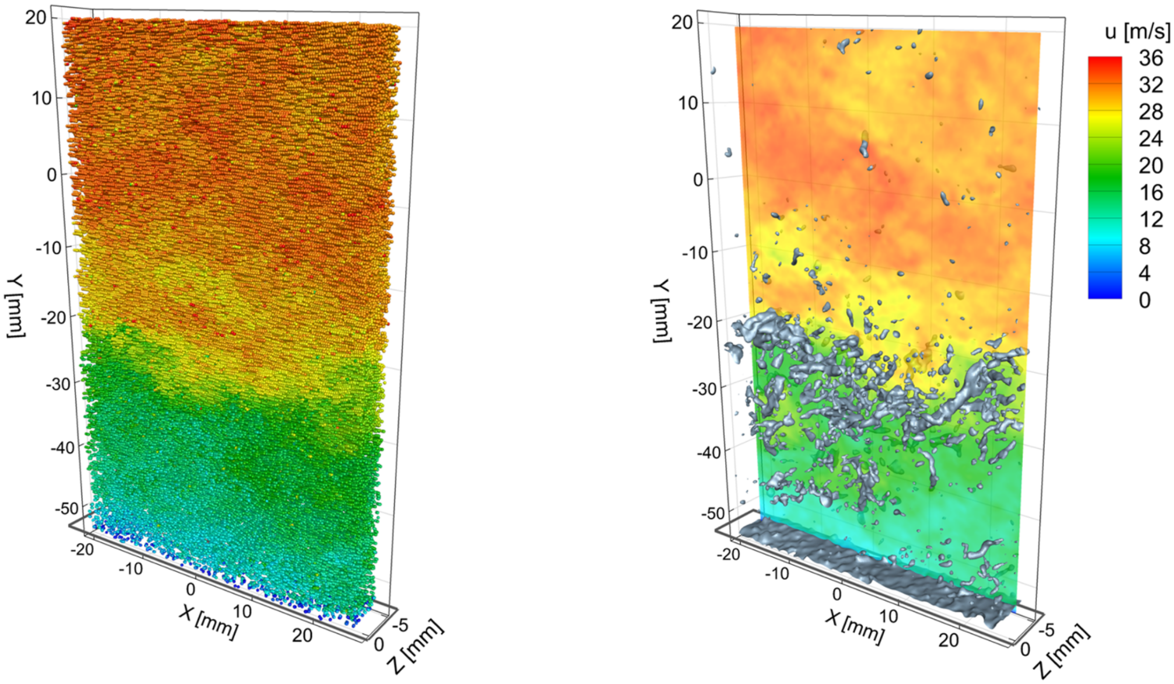

Figure 6. Instantaneous MP-STB result. Left: individual particle tracks; particle locations along the four pulses indicated by a spherical marker color-coded by the magnitude of the stream-wise velocity component. Right: FlowFit interpolation on a regular grid; is-surface of vorticity magnitude ($|\omega| = 7{,}000\ 1/s$) in gray.

The sequence of $20{,}000$ instantaneous track fields is exploited to obtain flow statistics in terms of boundary layer profiles of the average velocity components and turbulent fluctuations in the wall-normal direction. Five profiles are evaluated along the X direction; two-dimensional bins having a size of $10 \times 0.04\ mm^2$ along the X and Y direction respectively and encompassing the whole measurement domain along the Z axis are used to partition the measurement domain. Individual particle tracks are collected for each bin along the time sequence in an ensemble average sense; for each track the velocity and location at the mid-point of the four pulse time-sequence is considered.

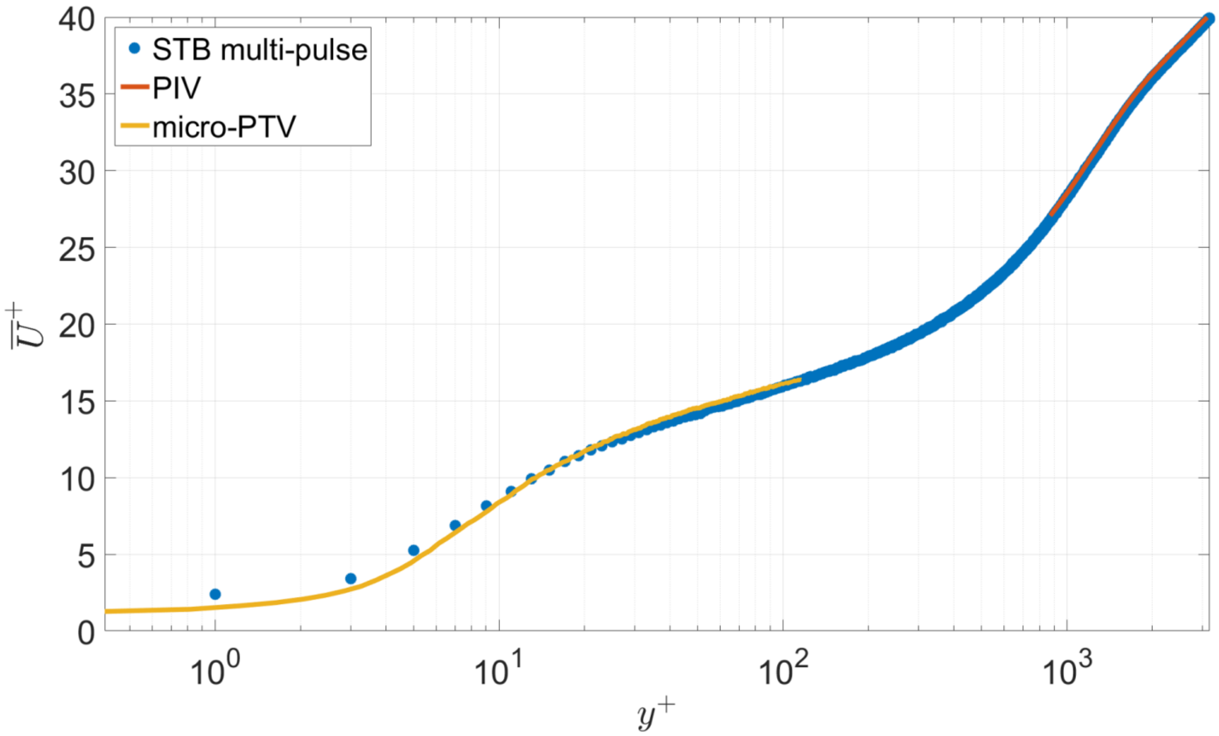

Figure 7. Mean normalized stream-wise velocity component along the wall normal direction (wall units).

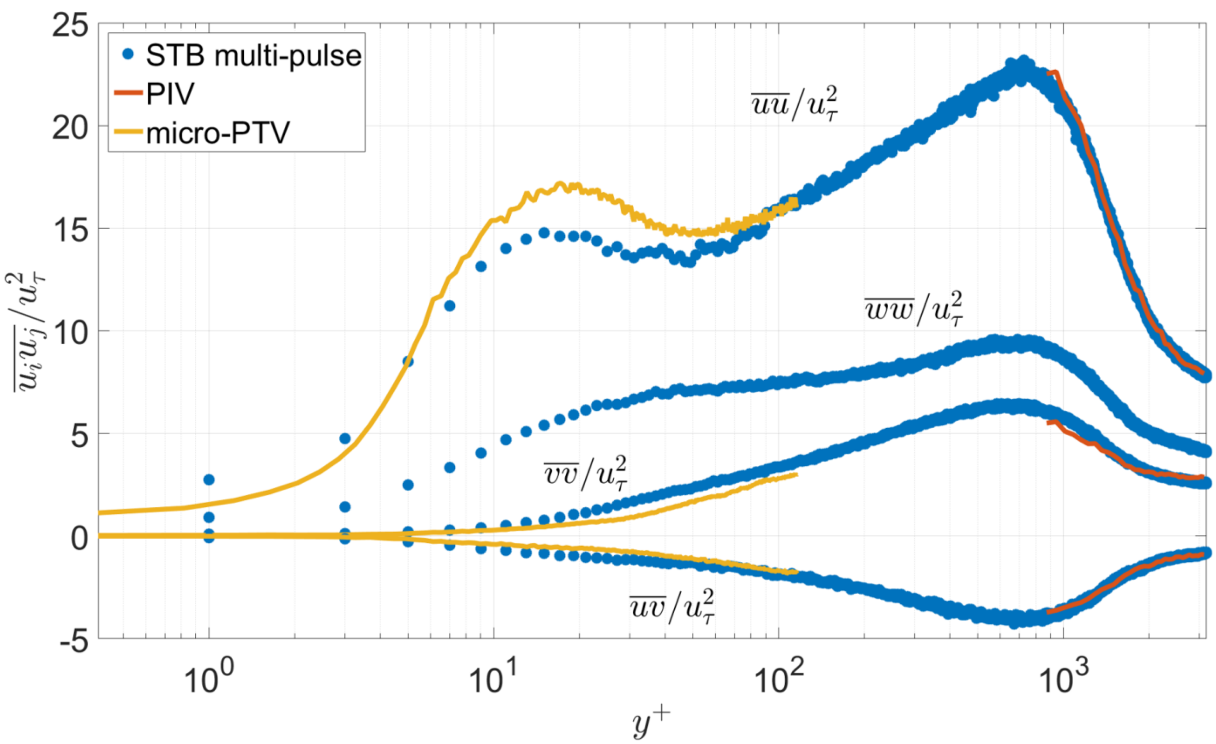

Figure 8. Reynolds stresses profiles along the wall normal direction (wall units).

Due to the structural vibrations of the wind-tunnel walls and of the camera systems, before the averaging process can be performed, a correction method is applied based on the instantaneous identification of the actual wall location. A detailed description of the correction methods is presented in [10].

The boundary layer profiles obtained from MP-STB are compared to those obtained from planar PIV and long-range micro PTV and are shown for the mean stream-wise velocity component and Reynolds stresses in Figure 7 and Figure 8 respectively. The wall-normal coordinate and velocities are expressed in wall-units; a viscous length of $0.02\,mm$ is estimated. Approximately 30,000 statistically independent samples are found in each bin for the MP-STB technique.

Results show that the multi-pulse particle tracking based technique is able to deliver accurate results over a wide range of spatial scales. Good agreement between the results from the different techniques is observed for $y^+ > 10$. It can be observed that the cross-correlation based technique suffers from the limitations in terms of spatial resolution posed by the finite size of the interrogation region. Conversely, when a high magnification approach is used (long range micro-PTV) a relatively small field of view can be investigated (approximately $20\,mm^2$), which limits the observation to the near-wall region ($y^+ < 100$). Both the micro-PTV and STB multi-pulse approach nicely resolve the inner peak of the stream-wise turbulence intensity located at $y^+ \sim 15$.

3.2 Turbulent boundary layer at 10 m/s

A turbulent boundary layer at $10\,m/s$ is investigated; the experiment is carried out in the 1m-Wind tunnel at DLR Göttingen. Illumination is provided by a pair of double-cavity BigSky CFR 400 lasers. The flow is seeded with DEHS (Di-Ethyl-Hexyl-Sebacate) droplets ($1\,\mu m$ diameter). A $75 \times 55 \times 4\,mm^3$ volume (in stream-wise, wall-normal and span-wise directions respectively) is illuminated and imaged by two three-camera imaging systems. The digital resolution is approximately $35\,px/mm$. Both PCO.Edge and FOX cameras (sensor size: $2048 \times 2048\,px$; pixel size $7.5\,\mu m$) are used; since the latter can be operated in three-frame mode (halving the resolution of the first two frames along one sensor), the timing-based pulse separation strategy shown in Figure 2 can be implemented. A relatively low seeding density of $0.02\,ppp$ is adopted. The experimental setup is shown in Figure 9.

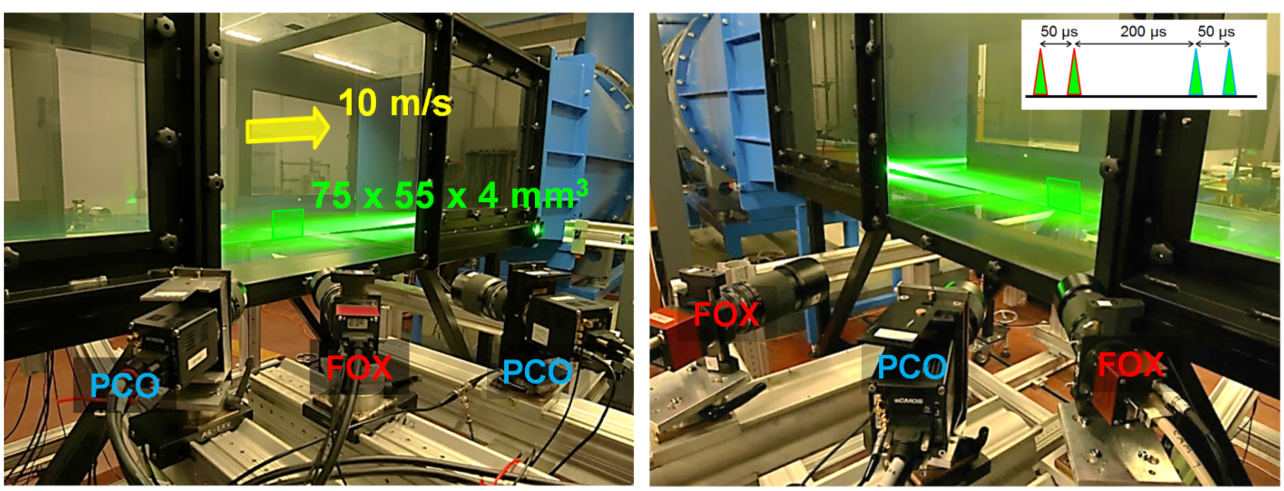

Figure 9. Experimental setup in the 1m-Wind Tunnel (DLR Göttingen); views from the right and left side of the test section (left and right respectively). The time diagram of the four pulses sequences is shown (top-right).

An uneven pulse separation is chosen in order to increase the dynamic range of the measurement; a time separation of $50\ \mu s$ has been chosen between the first- and last-two pulses, while a larger separation of $200\ \mu s$ is set between pulses two and three; $10{,}000$ four-pulse sequences have been recorded at a frequency of $10\ Hz$ in order to provide statistical convergence and allow for the evaluation of flow statistics.
An instantaneous MP-STB result is shown in Figure 10, where tracked particles are color-coded by the stream-wise component; the flow direction is aligned with the X axis, while the wall is located at $Y = 0\ mm$. Three STB iterations have been used here.
The 10,000 instantaneous track fields are analyzed by means of an ensemble average approach using one-dimensional bins of $14.5\ \mu m$ size along the wall-normal direction to generate boundary layer profiles; approximately three measurement points are found within a single wall unit ($y^+ \sim 42\ \mu m$). For each bin the statistics are evaluated over approximately $35{,}000$ independent samples.

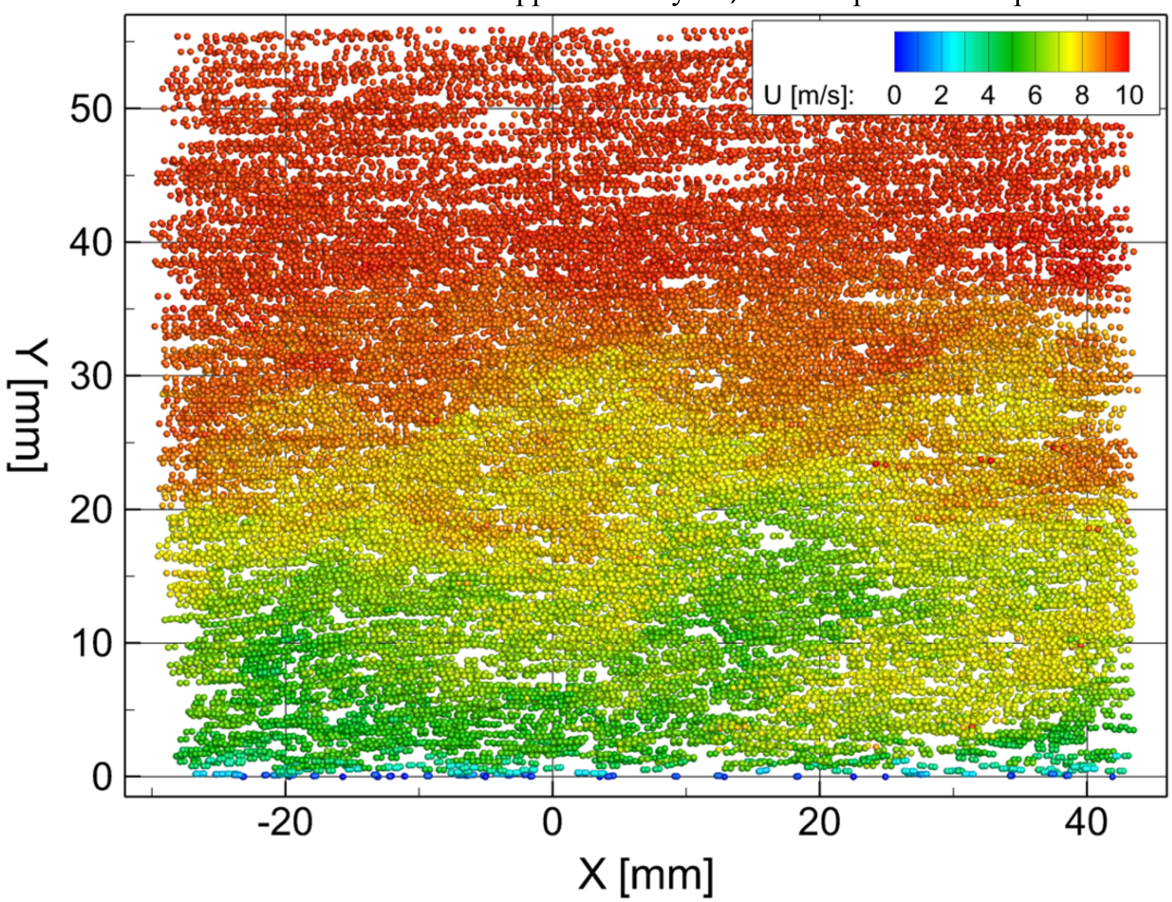

Figure 10. Approximately $10,000$ instantaneous tracked particles from MP-STB.

The profiles relative to the turbulent fluctuations are shown in Figure 11 together with the DNS results from [13]. Results show very good agreement with the DNS data; as expected a slightly higher noise level is found in the near wall region ($y^+ < 1.5$), where the lower flow velocity leads to lower particle displacements and, in turn, to a reduced dynamic range of the measurement.

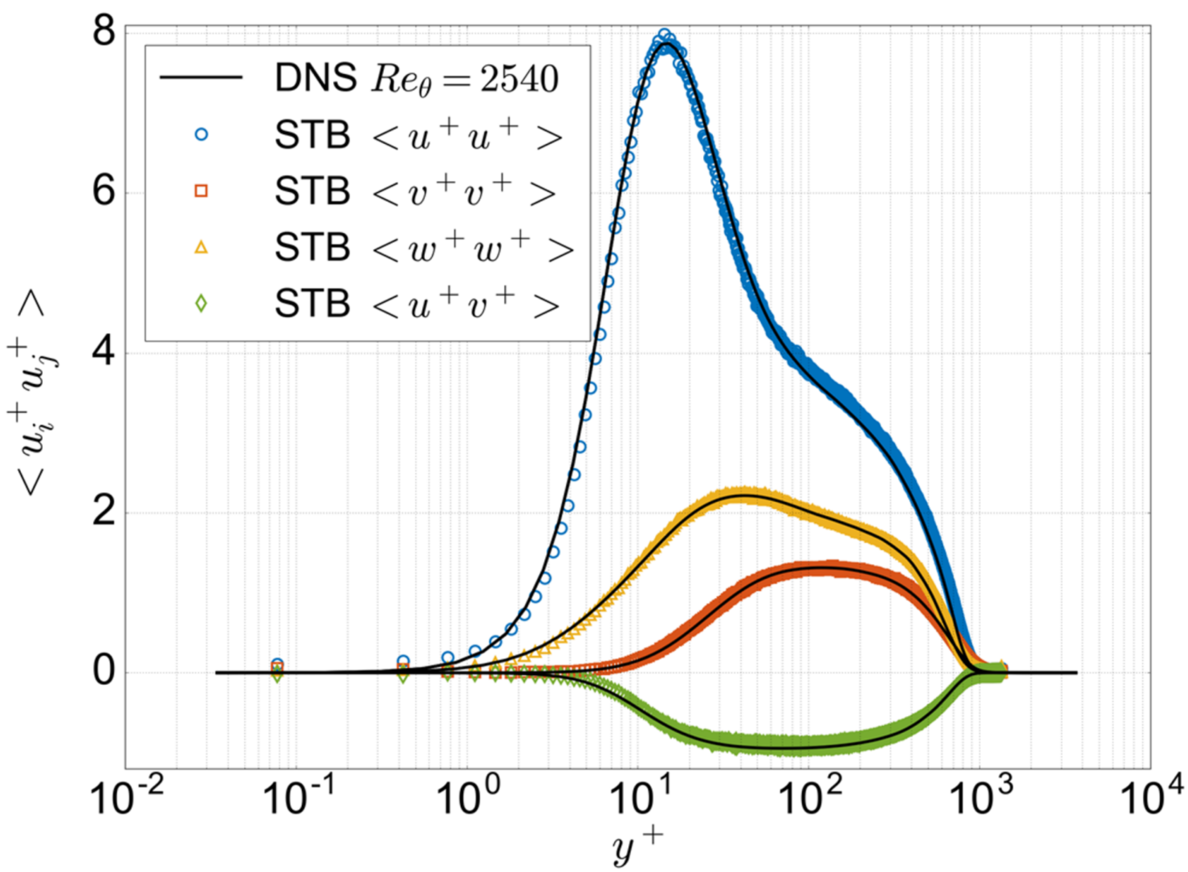

Figure 11. Mean profiles of turbulent fluctuation intensity along the wall normal direction.

3.3 Subsonic jet at Mach 0.84

A subsonic jet in air at Mach 0.84 is investigated by means of Multi-Pulse Shake-The-Box. The experiment is carried out in the anechoic test facility at the DLR Göttingen. The jet is issued by a round nozzle having an inner diameter of 15 mm. A multi-pulse setup obtained by the combination of two dual-frame acquisition systems was used to record tracer particle images within a volume of $90 \times 70 \times 10\ mm^3$ along the jet axial (X), radial (Y) and out-of-plane (Z) directions, respectively. The polarization based acquisition strategy described in Figure 1 is adopted. An uneven pulse separation is applied in order to maximize the measurement dynamic range; the first two pulses are separated by 1.25 μs while a larger separation of 3.75 μs is used between the second and a third pulse. The last two pulses are again recorded with a time separation of 1.25 μs.

Illumination is provided by two dual-cavity Quantel Evergreen Nd:YAG lasers (200 mJ pulse energy at 10 Hz) emitting horizontal and vertical polarized light.

The two imaging systems consisting each of four sCMOS PCO-Edge cameras, equipped with polarization filters to separate the four pulses onto the image sensor, Figure 12. Cameras, in Scheimpflug condition, are equipped with objective lenses having focal lengths of $f = 200\ mm$ and 180 mm; the f-number ($f_\#$) was set to 11. The digital resolution was approximately 33.6 px/mm.

As a consequence of the uneven spacing of the pulses, the maximum displacement of particle tracers is approximately 12 px and 37 px for the shorter and longer time interval respectively, resulting in maximum of approximately 61 px total particle shift.

A Laskin nozzle with a separate impactor was used to provide seeding of DEHS with a nominal particle diameter of 1 μm. The seeding was introduced upstream of the nozzle and the ambient air was also seeded enabling a homogenous distribution across the measurement volume. The symmetric camera setup ensures similar image quality between the two acquisition systems. The seeding concentration adopted for the experiment resulted in a particle image density of approximately $0.025 \div 0.05\, ppp$. For each measurement configuration, a total of 40,000 four-pulse sequences were recorded at a sampling frequency of 10 Hz.

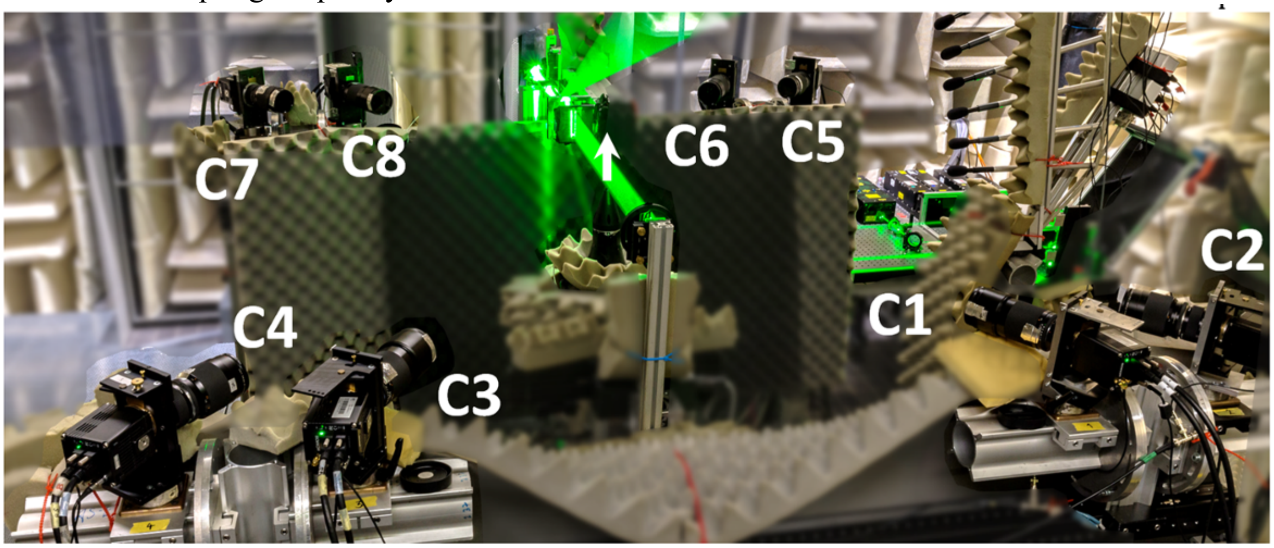

Figure 12. Experimental setup for the Multi-Pulse STB investigation of a subsonic jet at Mach 0.84.

For the present investigation three STB iterations have been performed for each four-pulse recording sequence. As a result, an average of $30{,}000 \div 90{,}000$ tracks, depending on the seeding density and individual camera image quality (due to the interdependency of scattering direction and polarization), could be successfully reconstructed for each instantaneous four-pulse recording sequence. It should be noted that the number of tracks refers to complete four-pulse tracks only; particles entering or leaving the investigated domain are not considered for sake of robustness of the measurement.
An instantaneous result from MP-STB is shown in Figure 13, where particle tracks are represented by the velocity vector displayed at the particle location and color-coded by the magnitude of the stream-wise velocity component. The FlowFit interpolation of the same instantaneous field is presented in Figure 13-right. The large sequence of 40,000 recordings enabled ensemble averaging with a bin size of $0.5 \times 0.5 \times 0.5\, px$ ($\sim 15\, \mu m$ or $0.001 \cdot Dj$) and thus provided ultra-high resolution statistical quantities of the jet flow (mean, turbulence intensities, Reynolds stresses etc.), Figure 14. Further details regarding the experimental setup and data processing can be found in [7].

3.4 Turbulent boundary layer with multi-exposed recordings

The acquisition strategy shown in Figure 3 is applied for the investigation of a turbulent boundary layer flow of 15 m/s carried out in the Cross- Wind Test Facility (SWG) at DLR Göttingen.
A single imaging system consisting of 8 PCO Edge sCMOS cameras ($2560 \times 2160\, px$, 6.5 μm pixel size) is used to image a $80 \times 100 \times 10\, mm^3$ volume in stream-wise, span-wise and wall-normal directions respectively.

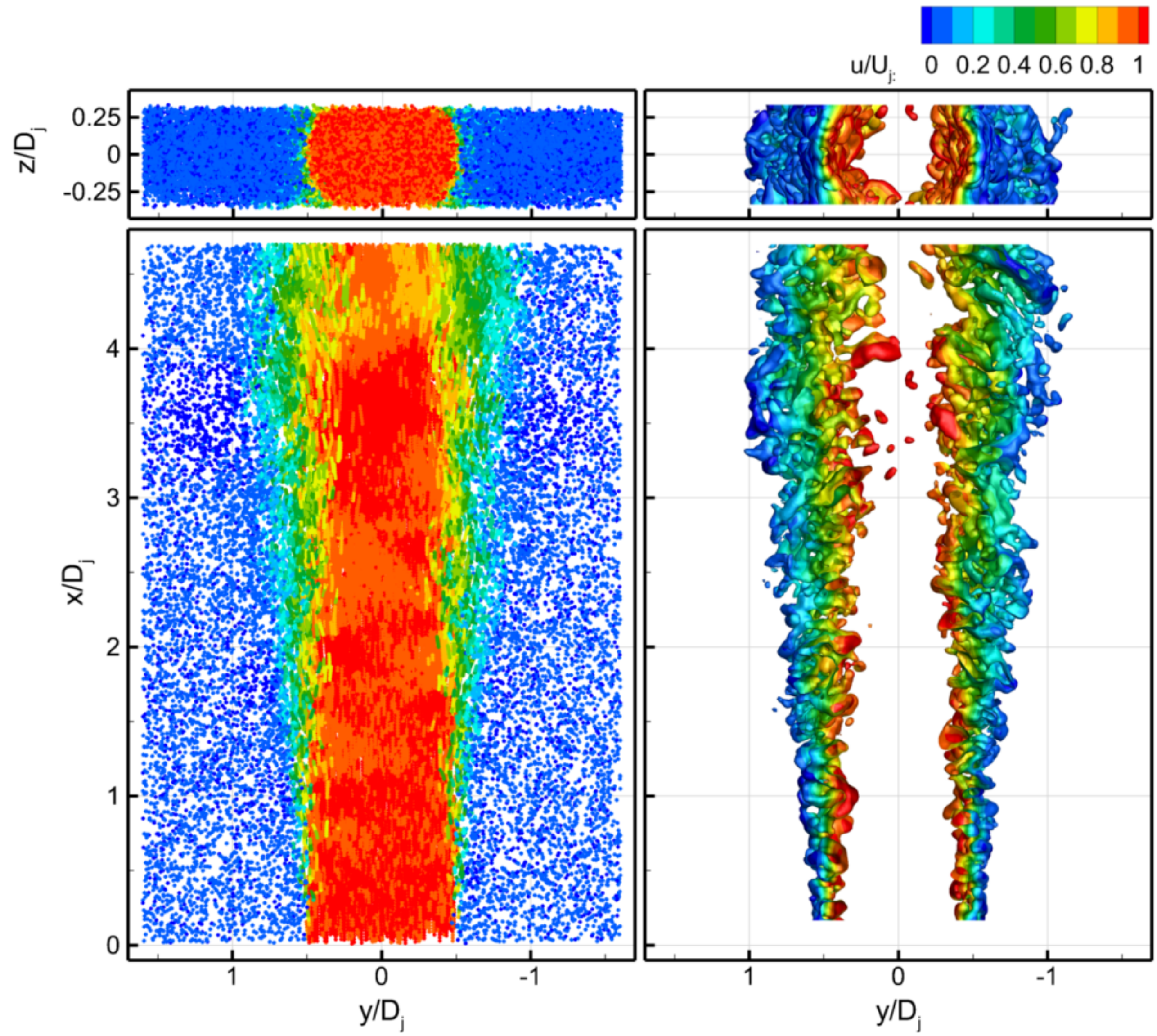

Figure 13. Left: approximately $40,000$ instantaneous tracks from MP-STB. Right: result interpolated onto regular grid (iso-surfaces of Q-criterion). Color-coding from axial velocity component.

The flow is seeded with DEHS particles and the digital resolution is approximately $23\ px/mm$. An uneven pulse distribution is chosen where pulses $1-2$ and $3-4$ are separated by $50\ \mu s$ while the time separation between pulses 2 and 3 is $150\ \mu s$.

An imaged seeding density of approximately $0.035\ ppp$ is applied; since each particle image appears twice within the recording, the corresponding image density for a single-exposed image is $0.0175\ ppp$. Given the size of the active portion of the sensor (i.e. illuminated region common to all cameras), approximately $54{,}000$ particle tracks are expected within the investigated domain.

The particle tracking approach described in [10][9] must be adapted to the case of multi-exposed recordings as each of the two particle objects reconstructed with IPR contains two realizations of the same particle distribution at two subsequent time instants. The tracking step is divided into two phases: the definition of the two-pulse track candidates and the identification of the four-pulse tracks.

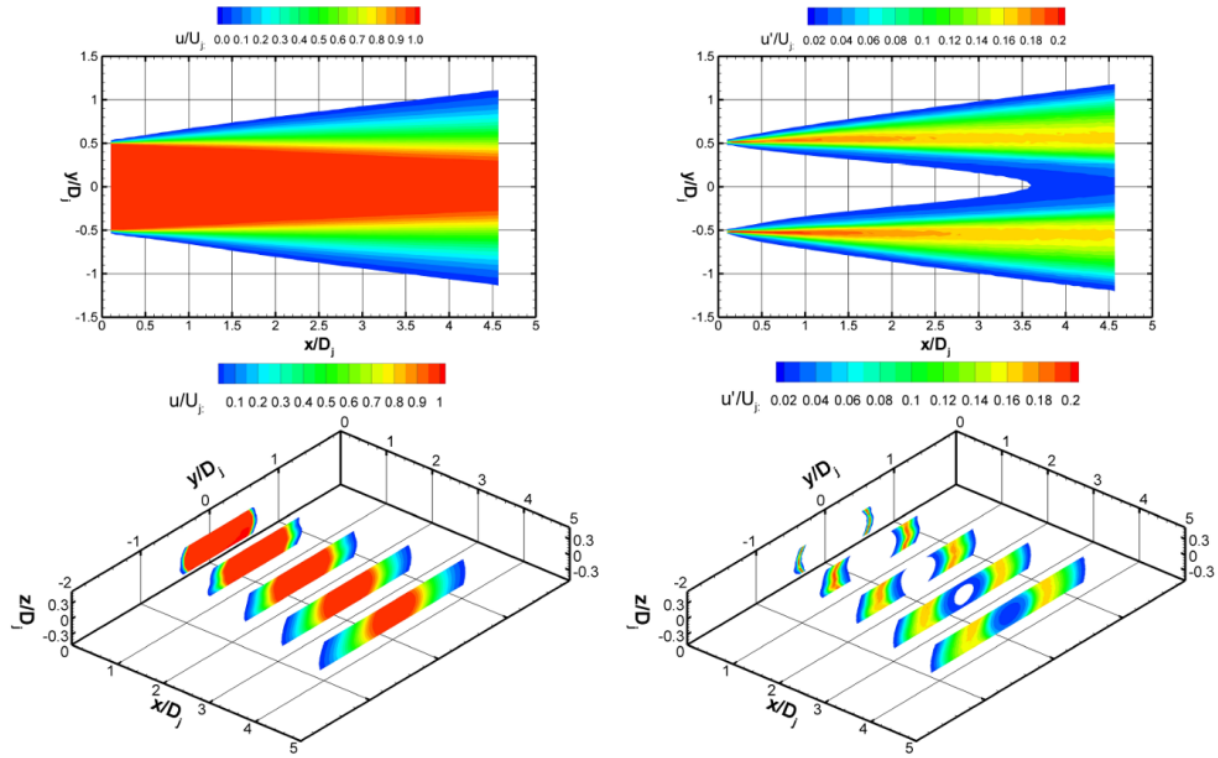

Figure 14. Three-dimensional flow statistics from ensemble averaging of 40,000 instantaneous track fields from MP-STB.

Due to the double-exposed particle images, no knowledge of the particle direction is available; as a consequence, for each couple of particles within the same IPR object (i.e. recording), two possible two-pulse track candidates are (potentially) created. Each track candidate is linearly extrapolated at the mid-time-point of the sequence; forward extrapolation is applied for pulses $1-2$ and backward for pulses $3-4$. The ambiguity on the particle direction is solved during the combination of the two-pulse candidates into four-pulse tracks; in fact only the candidates corresponding to the actual particle direction will produce mid-point locations falling within the chosen search region.

Once the coupled two-pulse candidates are found, the location of the four particles along the track is fitted by means of a second order polynomial fit; in case multiple four-pulse track candidates are found which share one or more particle (a situation commonly encountered when adopting large search radiuses), the candidate showing the lowest residual from a linear fit of the particles location along the sequence is chosen (following the approach proposed by [12]). The use of the mid-point prediction to combine the two-pulse candidates is justified by the choice of an uneven pulse separation, where pulses 2 and 3 are separated by a time interval typically 3 to 4 times larger than pulses $1-2$ and $3-4$. When the flow speed results in particle displacements lower than a single particle image diameter ($\sim 2.5\ px$), the particle images of the same tracer on the double-exposed frame start overlapping eventually leading to a single particle image. In order to track these particles, the last STB iteration is performed identifying two-pulse tracks between the particles at pulses $1-2$ to the ones at $3-4$.

Four STB iterations have been applied for the analysis of the present data; a total number of approximately 49,150 particles are reconstructed by the iterative Multi-Pulse STB, corresponding to roughly 90% of the expected actual number of particles.

An instantaneous result from STB is presented in Figure 15; the scattered results extracted from the track fit at the mid-point of the trajectory are interpolated onto a regular grid. The spatial gradients can be evaluated from the cubic spline fit and used to identify the 3D vortical structures within the boundary layer.

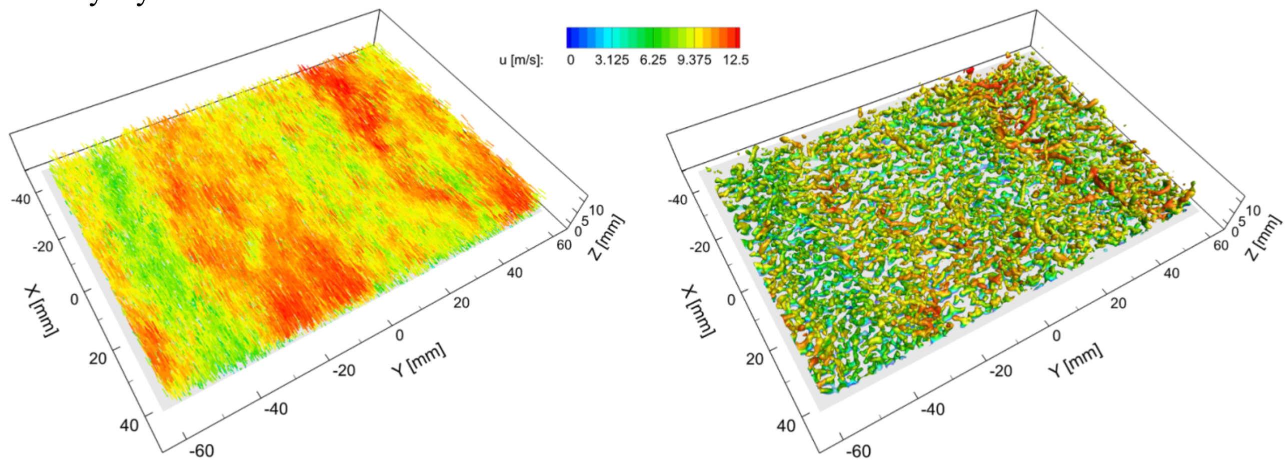

Figure 15. 10 Instantaneous Multi-Pulse STB result with multi-exposed frames; wall indicated by gray plane. Left: approximately 49,000 tracks color-coded by the stream-wise velocity component. Right: FlowFit interpolation onto regular grid; iso-surface of Q-criterion colored by stream-wise velocity component.

4 Conclusions

The Multi-Pulse Shake-The-Box algorithm is applied to four-pulse recordings from multi-camera 3D imaging system to perform Lagrangian particle tracking in high-speed flows. Several acquisition strategies for the recording of multi-pulse sequences have been proposed, and presented in the present study. The iterative processing strategy adopted for the analysis (reconstruction and tracking) of MP-STB data is described. Four different applications of the MP-STB technique are presented; the main experimental and processing parameters are described and results in terms of instantaneous tracks and flow statistics are shown. Results show the suitability of the Lagrangian particle tracking algorithm for the investigation of turbulent flows in a wide range of flow conditions and velocities.
Furthermore, the use of multi-exposed recordings allows for the simplification of the imaging system, as well as for the reduction of the experimental setup costs and required optical access to the investigated domain. These aspects are of particular interest when dealing with the investigation of aerodynamically relevant high-speed flows in industrial facilities.

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