Experimental and numerical study of geometry-induced separation of a turbulent boundary layer

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Outline

- Motivation
- Experimental and numerical methods
- Experiment in the One-Meter wind tunnel Göttingen (1MG)
  - Design of the experiment and numerical study
  - Experimental configuration and test conditions
  - Experimental setup
    - 2D Lagrangian Particle Tracking (LPT) by *Shake-The-Box* (STB)
    - Temperature-Sensitive Paint (TSP)
- Preliminary results
- Summary

Motivation

The Reynolds-Averaged Navier-Stokes (RANS) equations and the corresponding RANS turbulence models are the current “bread-and-butter” of the aerospace industries

- Design and analysis
- Complex cases in reasonable turn-around times with limited resources
- But: edge-of-envelope and off-design capabilities limited

  → needed for new designs and certification-by-analysis

- Weak link: severe limitations of closures in RANS turbulence models
  - Thorough Verification and Validation (V&V) is a must for these approaches

Validation: Determination of the degree to which a model accurately represents the real world, or simply: “How good is the model?”

RANS turbulence modeling is

- considered trustworthy for many attached flows
- not trusted for separated flows

Motivation

- The *NASA's 40% Challenge and CFD Prediction Error Assessment Workshop 2018* and further studies showed discrepancies in the capabilities of RANS turbulence models to predict the shape and size of turbulent separation bubbles
- Contradictive conclusions from the comparisons of experimental and numerical results for standard reference test cases (*Backward-Facing Step (BFS) Flow* and *NASA Hump Flow*)

https://turbmodels.larc.nasa.gov/nasa40percent.html

D.M. Driver, H.L. Seegmiller, H. L. (1985) *AIAA J.* 23(2): 163-171.

D. Greenblatt, K.B. Paschal, C.-S. Yao, J. Harris, N.W. Schaeffler, A.E. Washburn (2006) *AIAA J.* 44(12): 2820-2830.

B. Eisfeld (2022) *Phys. Fluids* 34: 025123.

- To enable reliable turbulence model validation and modeling extensions, high-fidelity experimental data are needed → design of a new experiment to be performed in two facilites within the DLR project *ADaMant*
  - Focus on geometry-induced separation in a turbulent boundary layer at nearly-zero pressure gradient
  - Implementation of advanced optical measurement techniques (2D LPT by STB and TSP)

Experimental and numerical methods
2D Lagrangian Particle Tracking (LPT) by *Shake-The-Box* (STB)

- Prior to *ADaMant*: optical measurement of BFS-induced separation via PIV or tomographic PIV (spatial filtering)
- 3D-LPT by STB enables the accurate tracking of particles in large numbers
- Application of (regularized) interpolation yields time- and space-resolved fields of velocity, acceleration and pressure
- 2D tracking scheme implemented within *ADaMant* ("*2D-STB*")

For details on the STB technique: see talk by D. Schanz on **Sept. 21 at 14:40** (within *XDC final workshop*)

D. Schanz, S. Gesemann, A. Schröder (2016) *Exp. Fluids* 57: 70.

Experimental and numerical methods
Surface temperature measurements via *Temperature-Sensitive Paint* (TSP)

- Based on a coating with embedded temperature-sensitive molecules, which is applied on the surface of interest
- TSP enables the space- and time-resolved measurement of the surface temperature distribution
- Aim in *ADaMant*: identification of critical lines (mainly: turbulent flow reattachment) via analysis of time-resolved TSP data
- Study of the surface temperature statistics and estimation of the celerity of propagation of temperature perturbations (directly related to skin friction)

For general information on the TSP technique:
see talk by N. van Hinsberg on **Sept. 21 at 15:00**

M. Miozzi, A. Capone, M. Costantini, L. Fratto, C. Klein, F. Di Felice (2019) *Exp. Fluids* 60: 13
M. Miozzi, F. Di Felice, C. Klein, M. Costantini (2020) *Exp. Therm. Fluid Sci.* 110: 109913

Experimental and numerical methods
SSG/LRR-ω turbulence model in the DLR TAU code

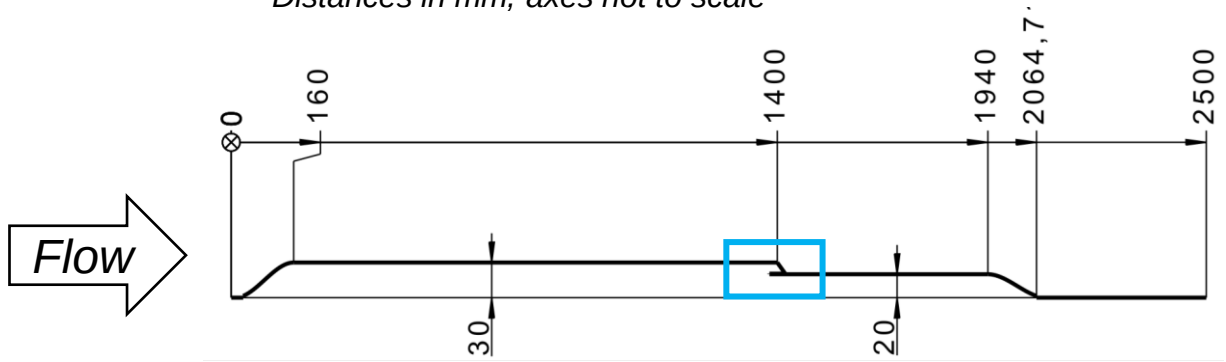
- Advanced Reynolds-Stress turbulence Model (RSM) relying on 7 additional transport-equations for the Reynolds stresses (6) and the length-scale equations (1).
- Developed by DLR and routinely used in aerospace industries and research institutes (e.g. Airbus, Dassault Aviation, NASA,…)
- Accurate prediction of complex flow phenomena on relevant aerodynamic configurations
- Extended for Adverse Pressure Gradient (APG) flows to improve the prediction of pressure-induced separation.

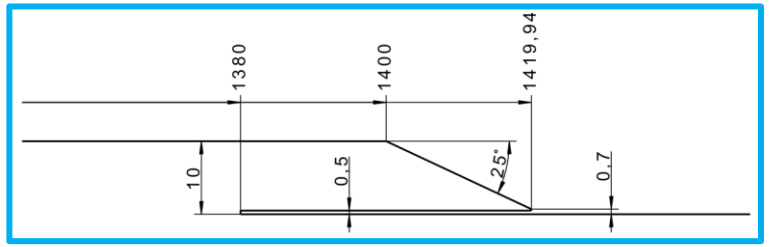
B. Eisfeld, C. Rumsey, V. Togiti (2016) *AIAA J.* 54(5): 1524-1541.
T. Knopp, N. Reuther, M. Novara, D. Schanz, E. Schülein, A. Schröder, C.J. Kähler (2023) *Flow Turb. Combust.* 111: 409-438.

Design of the experiment and numerical study
Geometry variation and model

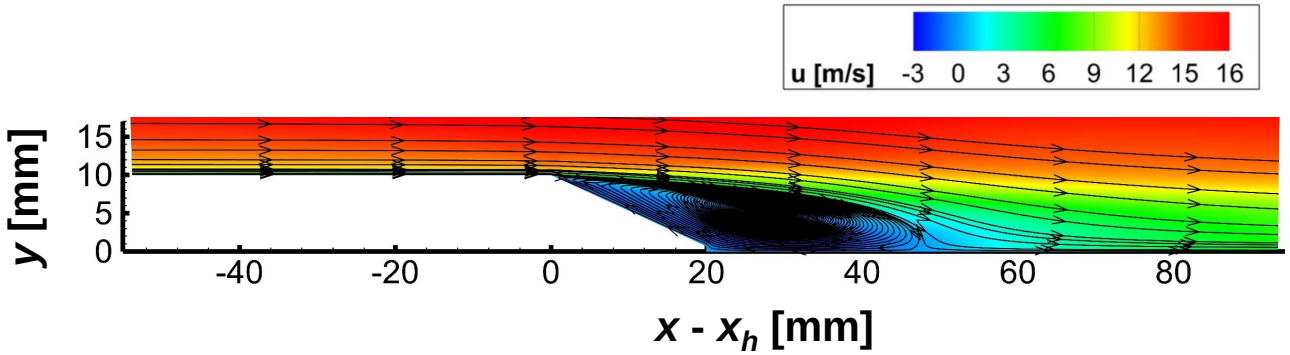
- Use of wind-tunnel bottom wall to generate a simple, robust model geometry
- Design parameters:
  - h/δ_{99} = 0.4, Re_{xh} up to $2.7 \cdot 10^6$
  - Highest Re_{xh} similar to that studied in the *BFS Flow experiment*
- Variation of geometry to investigate cases with and without secondary separation bubbles: actual BFS and backward-facing ramps
- Simulations performed using the DLR TAU code with SSG/LRR-ω turbulence model
- Hexahedral meshes for CFD simulations generated using Pointwise (wind-tunnel walls considered)
- Grid points in each 2D plane: 583 × 400

Distances in mm; axes not to scale





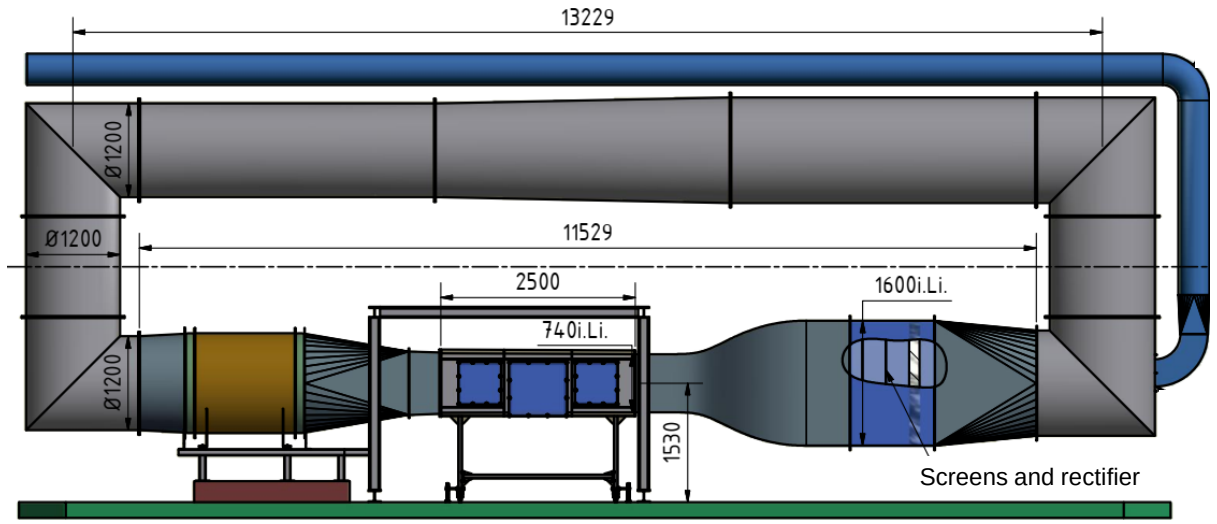
Detail of 25° ramp



Experimental configuration and test conditions

Wind tunnel, BFS configurations and Reynolds numbers

- DLR One-Meter wind tunnel Göttingen (1MG)
- Low-speed (max. U_∞ = 70 m/s)
- Operated with the closed test section (turbulence level of the order of 0.2 %)



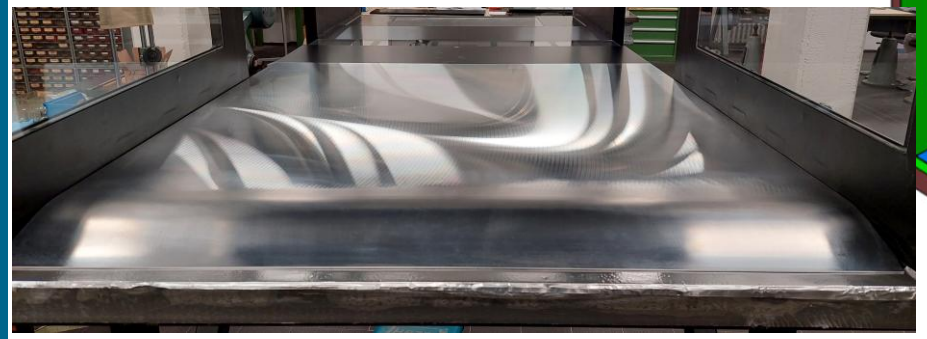
Distances in mm

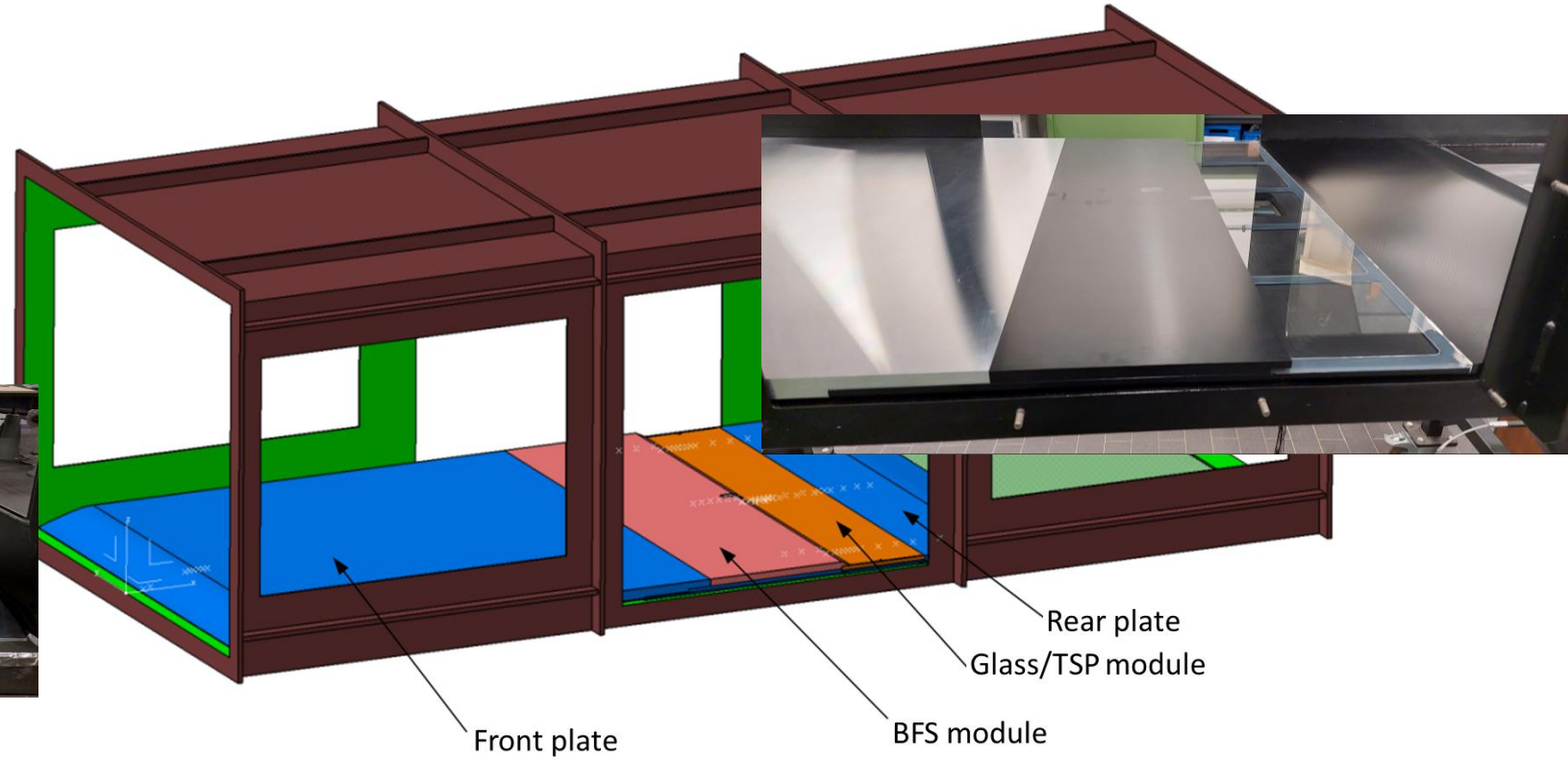
- 3 model configurations (all referred as “BFS”):
  - backward-facing step (90°)
  - 45° backward-facing ramp
  - 25° backward-facing ramp
- 4 freestream speeds:

U_∞ [m/s]	Re_{xh}	Re_h
13.8	$1.2 \cdot 10^6$	8,800
18.1	$1.6 \cdot 10^6$	11,500
24.6	$2.2 \cdot 10^6$	15,600
30.6	$2.7 \cdot 10^6$	19,400

Experimental configuration and test conditions
Model installation

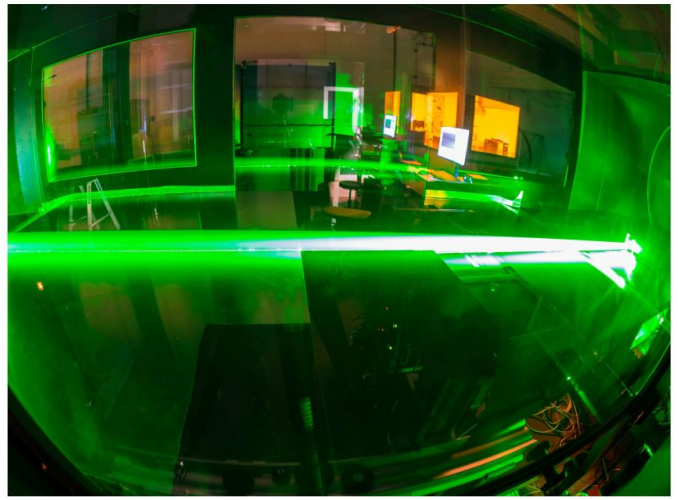
- Turbulent boundary layer over the bottom side of the 1MG test section
  - Transition fixed at x = -0.56 m (0.7 mm thick zig-zag tape)
- 3 exchangeable modules ("BFS modules") to investigate the 3 BFS configurations
- Exchangeable glass and TSP modules used for 2D-STB and TSP measurements, respectively
- BFS located at x_h = 1.4 m
- BFS height: h = 10 mm

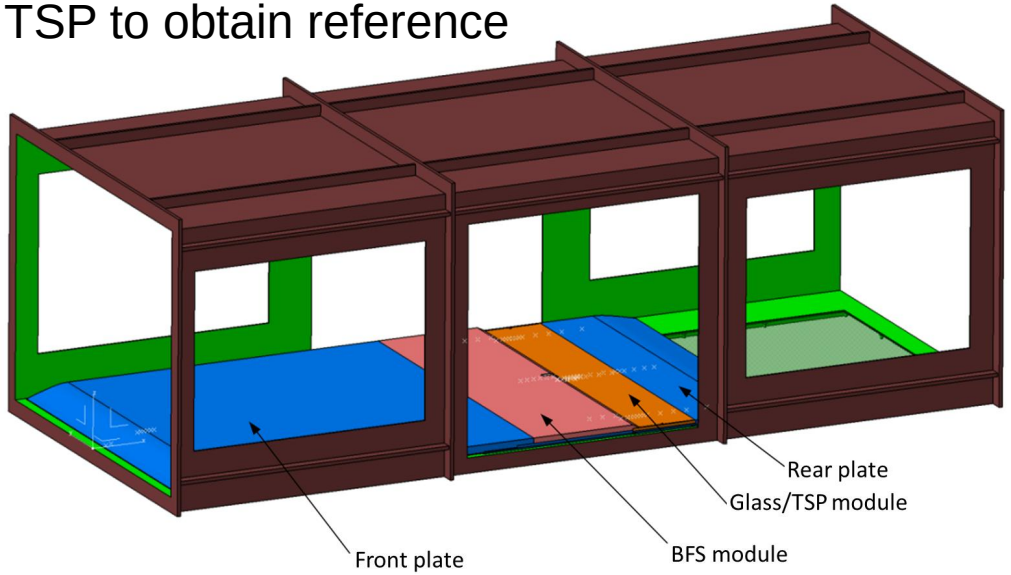


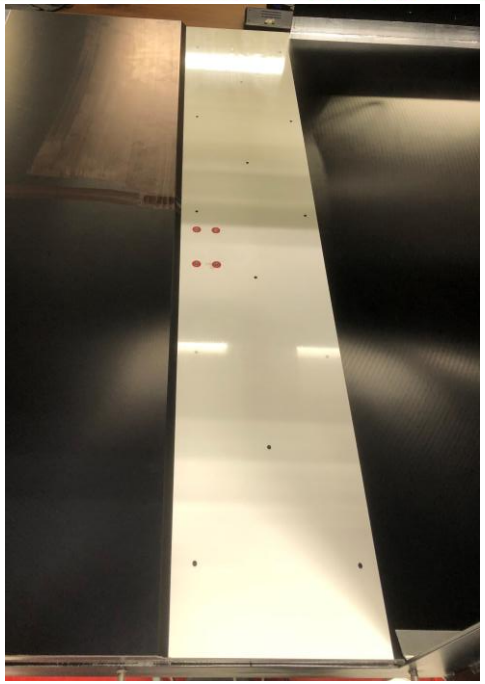


Experimental setup
Overview

- 2D-STB for the determination of the flow quantities and statistics around the BFS
- TSP for the measurement of the surface temperature field downstream of the BFS
- Three pressure tap rows for the measurement of the steady pressure distribution along the model
- Microphones (4) for the detection of the pressure fluctuations downstream of the BFS
- Thermocouples below the TSP to obtain reference temperatures



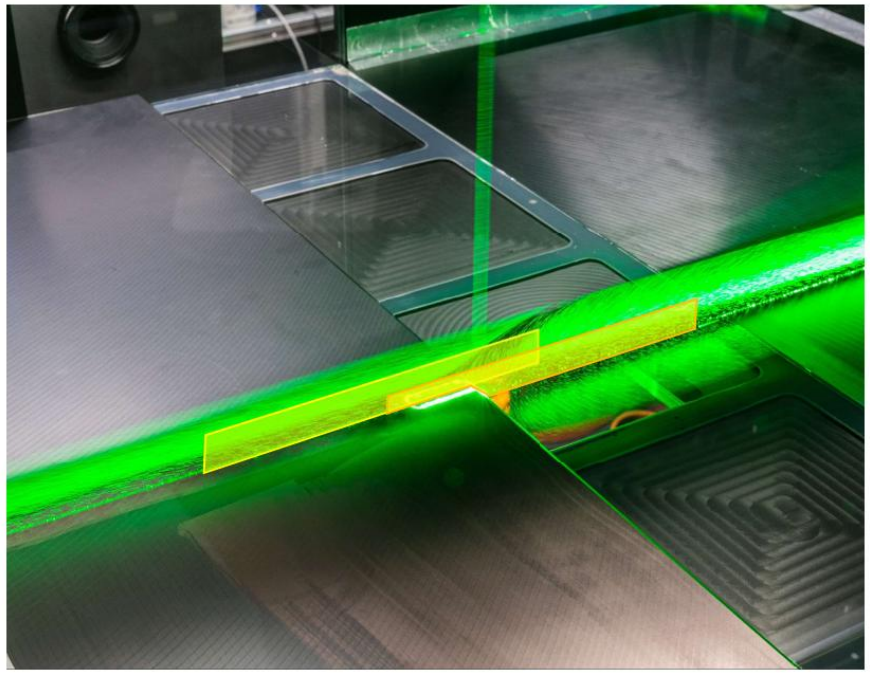


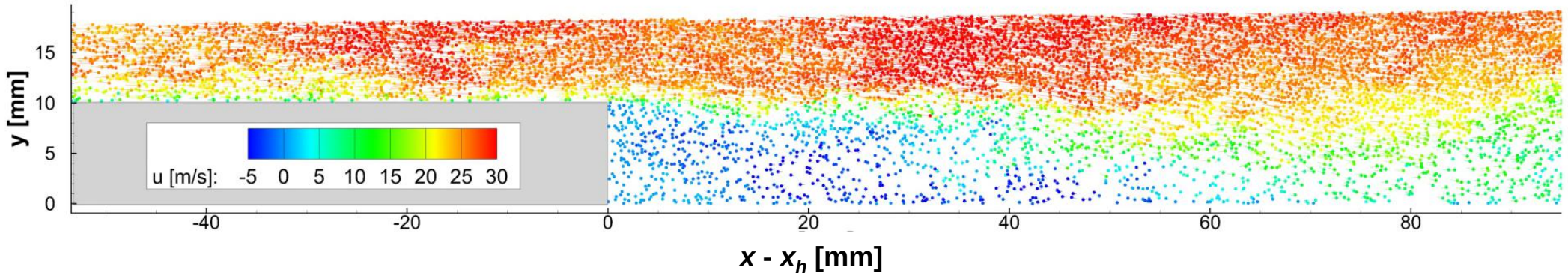


Experimental setup
2D-STB measurements

- Two Phantom V2640 cameras covering the BFS region around x_h = 1.4 m (here: camera capturing x = 1.345–1.495 m)
- Images of 2048 × 288 pixels^2 acquired at 20-40 kHz
- Photonics Industries DM200 high-speed laser
- DEHS droplets (approx. 2 µm size) used as seeding particles
- Each measurement run recorded 1,600 *chunks* with 100 consecutive images each
- 4-6 runs per configuration and velocity

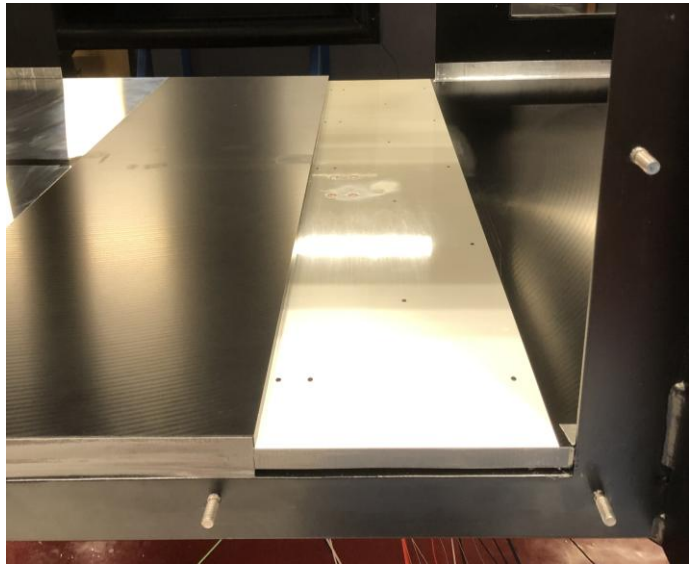
  → Up to 9,600 temporally independent flow situations
- 6,000-13,000 particles tracked in each image
- Spatial precision of particle tracks: < 8 µm (4 µm)



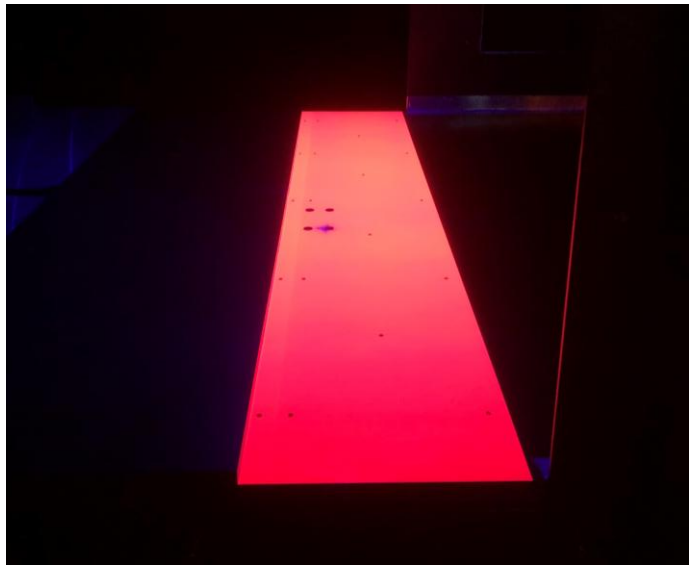


Experimental setup
TSP measurements

- TSP module composed of a laminate manufactured from fiber-reinforced plastic
  - Current-carrying carbon layer used to enhance the flow-induced temperature signatures at the wall
  - TSP and heating layers integrated into the lamination process
- Europium-based TSP layer
  - Excited via high-power LEDs at λ_{ex} ~ 400 nm
  - Light emitted by the TSP (λ_{em} ~ 615 nm) captured by a high-speed camera at 1 kHz frame rate
- TSP region covers the full span
  - Area captured by the TSP camera: 0.19 × 0.65 m^2 (streamwise × spanwise)
  - Spatial resolution of (mapped) TSP data: 0.6 mm
- Pressure taps and microphones are also integrated into the TSP module



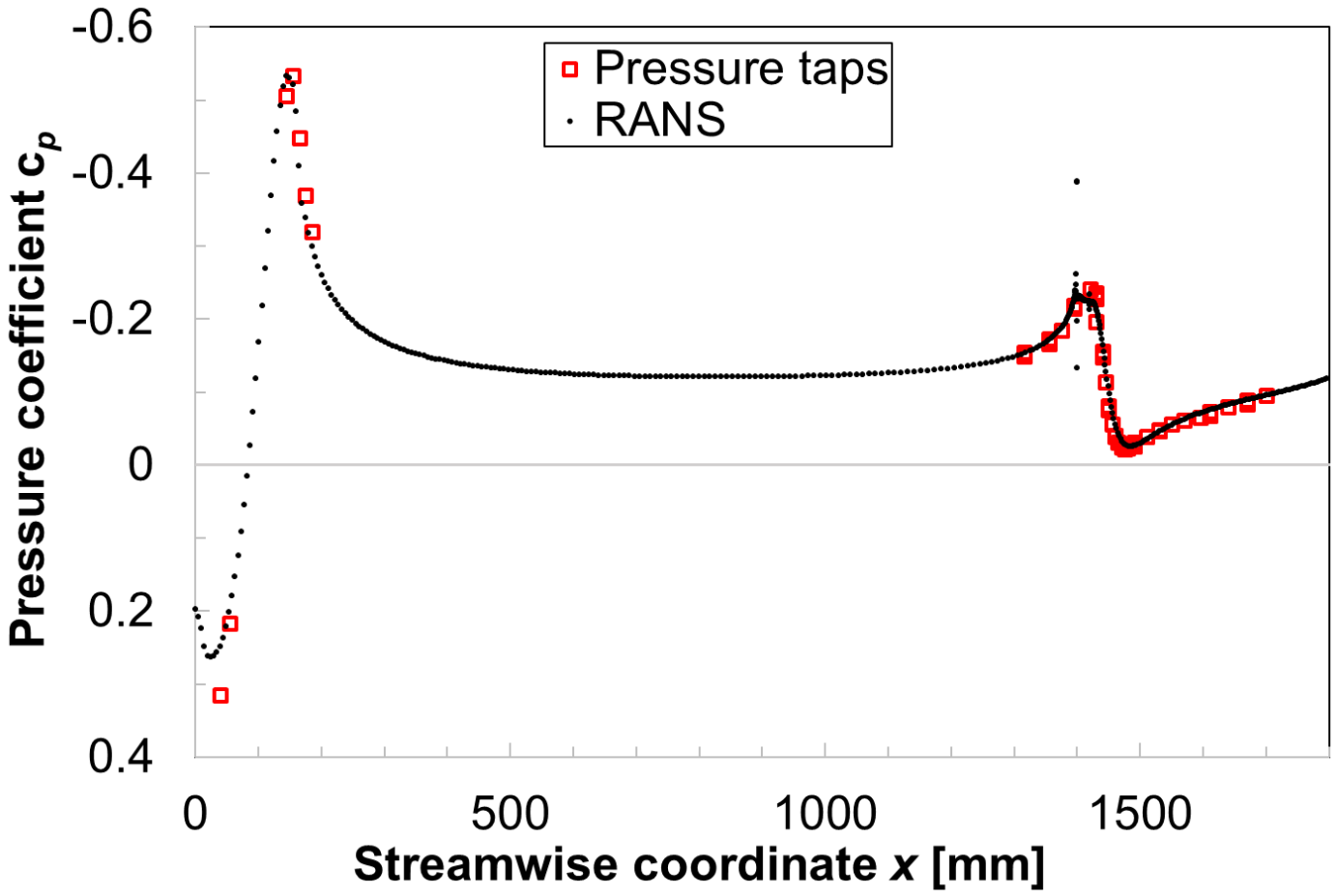
Room light on, LEDs off



Room light off, LEDs on

Preliminary results
Comparison of surface pressure data

- Distribution of pressure coefficient measured with 25° BFS at U_∞ = 18.1 m/s
- Comparison with RANS computations



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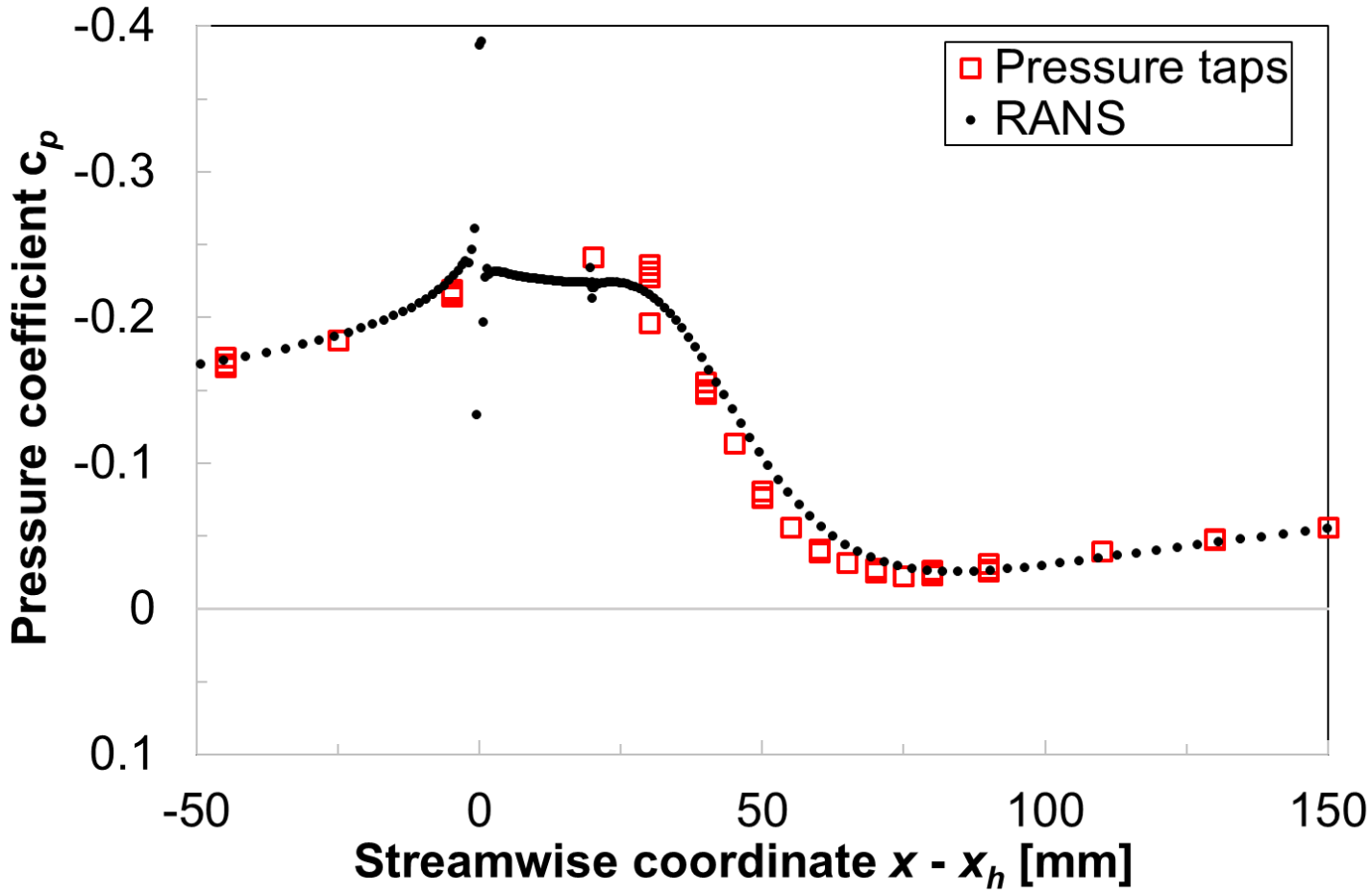
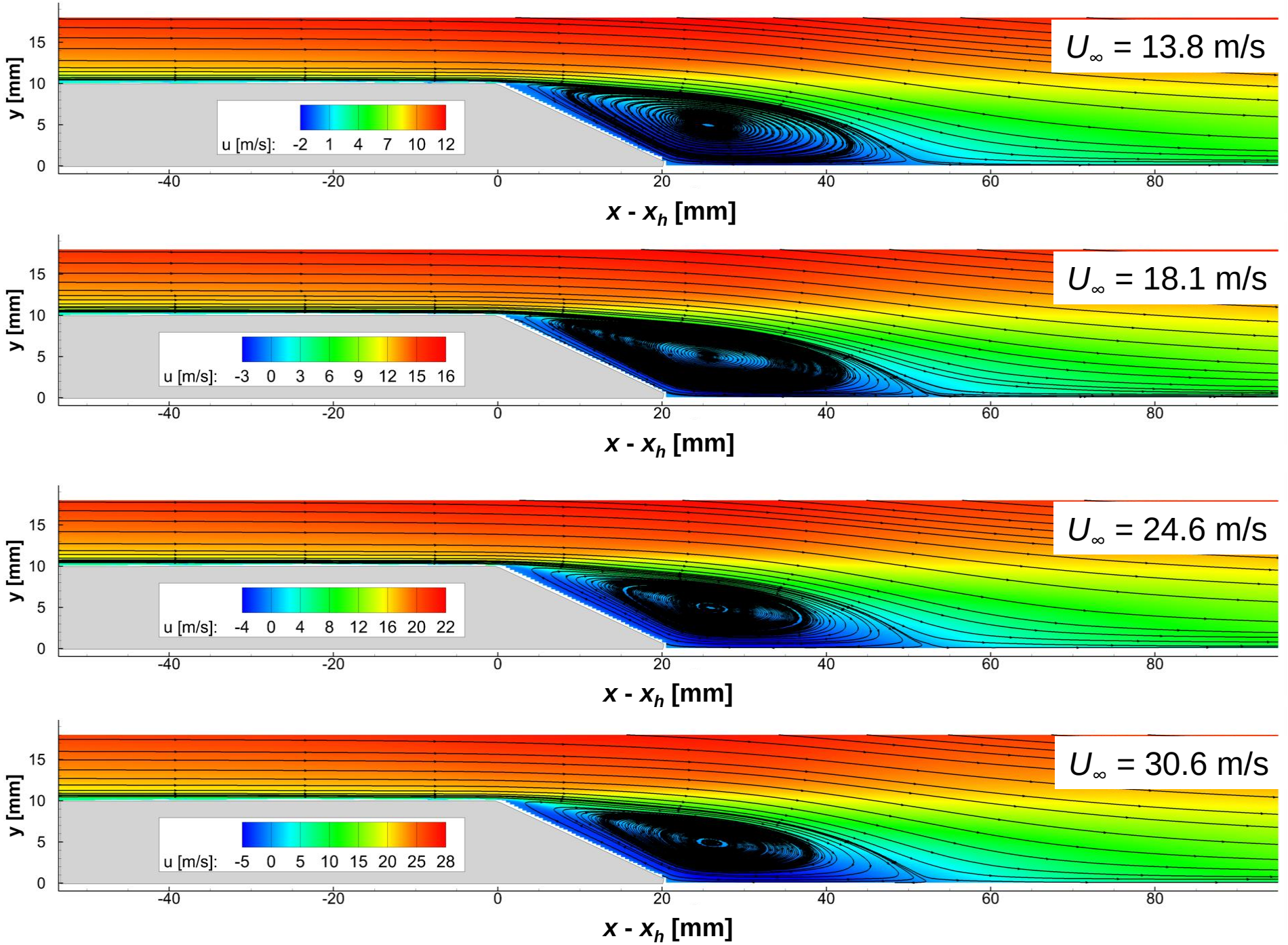


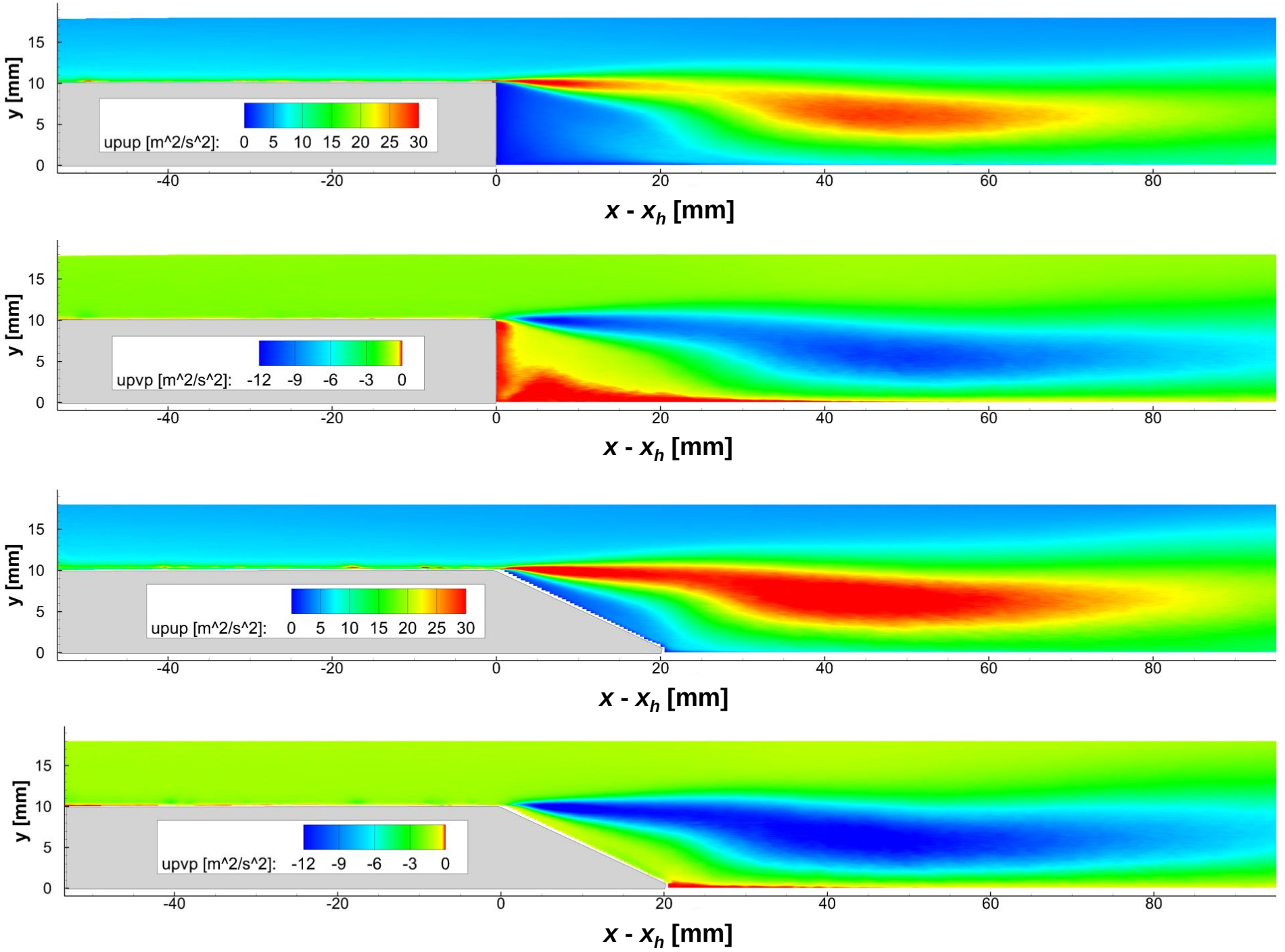
2D-STB results: *u*-component and streamtraces

- 25° BFS configuration
- Variation of Re
- Binning: time-average over one single run (1,600 * 100 images)
- Bin size:
  - 500 µm streamwise
  - 50 µm wall-normal
- 7,000 - 35,000 entries per bin



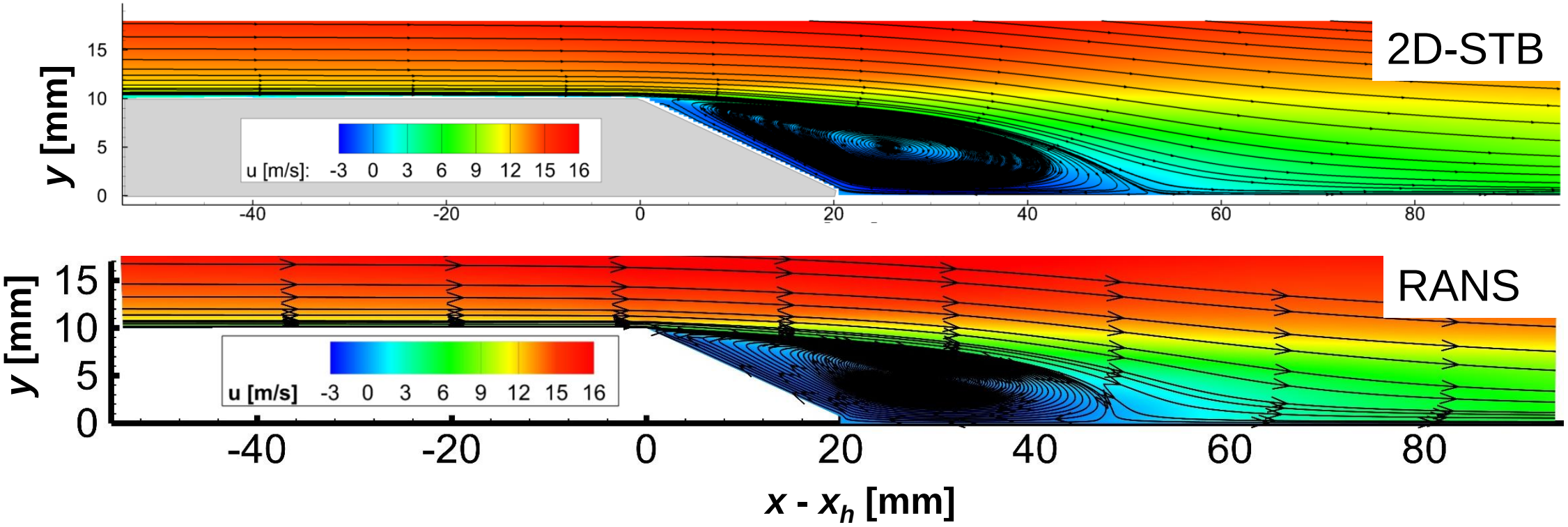
2D-STB results: Reynolds stresses

- 90° and 25° BFS configurations
- U_∞ = 30.6 m/s
- *u*'*u*' and *u*'*v*' shown
- Binning: time-average over one single run (1,600 * 100 images)
- Bin size:
  - 500 µm streamwise
  - 50 µm wall-normal
- 7,000 - 35,000 entries per bin



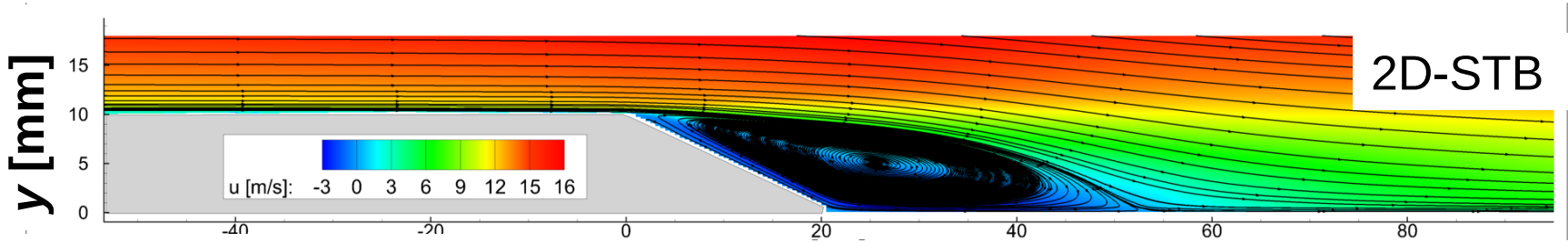
Preliminary results
Comparison of separated flow and reattachment

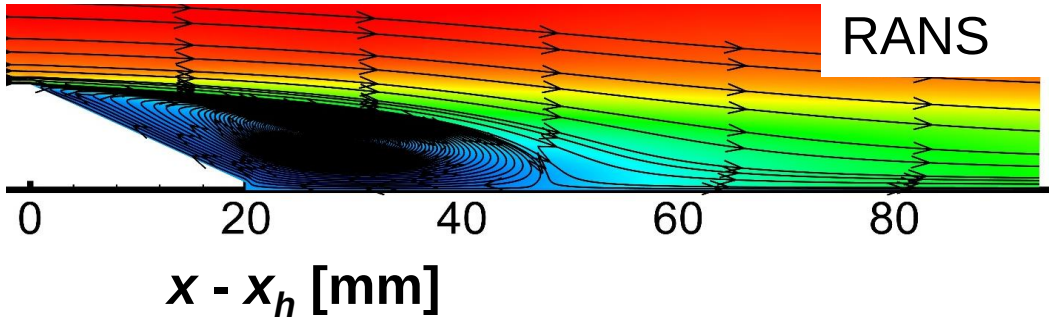
- 25° BFS configuration at U_∞ = 18.1 m/s:
  - *u*-component and streamtraces

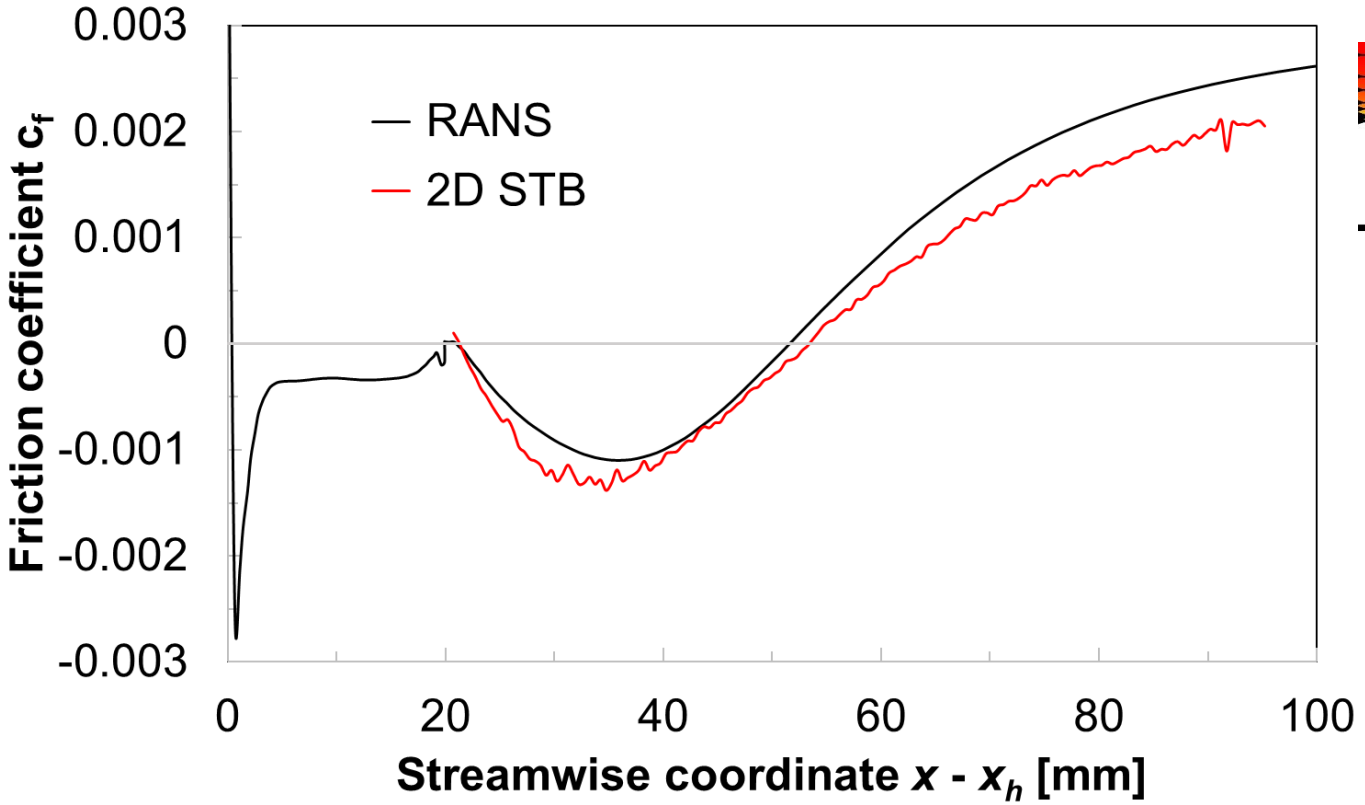


Preliminary results
Comparison of separated flow and reattachment

- 25° BFS configuration at U_∞ = 18.1 m/s

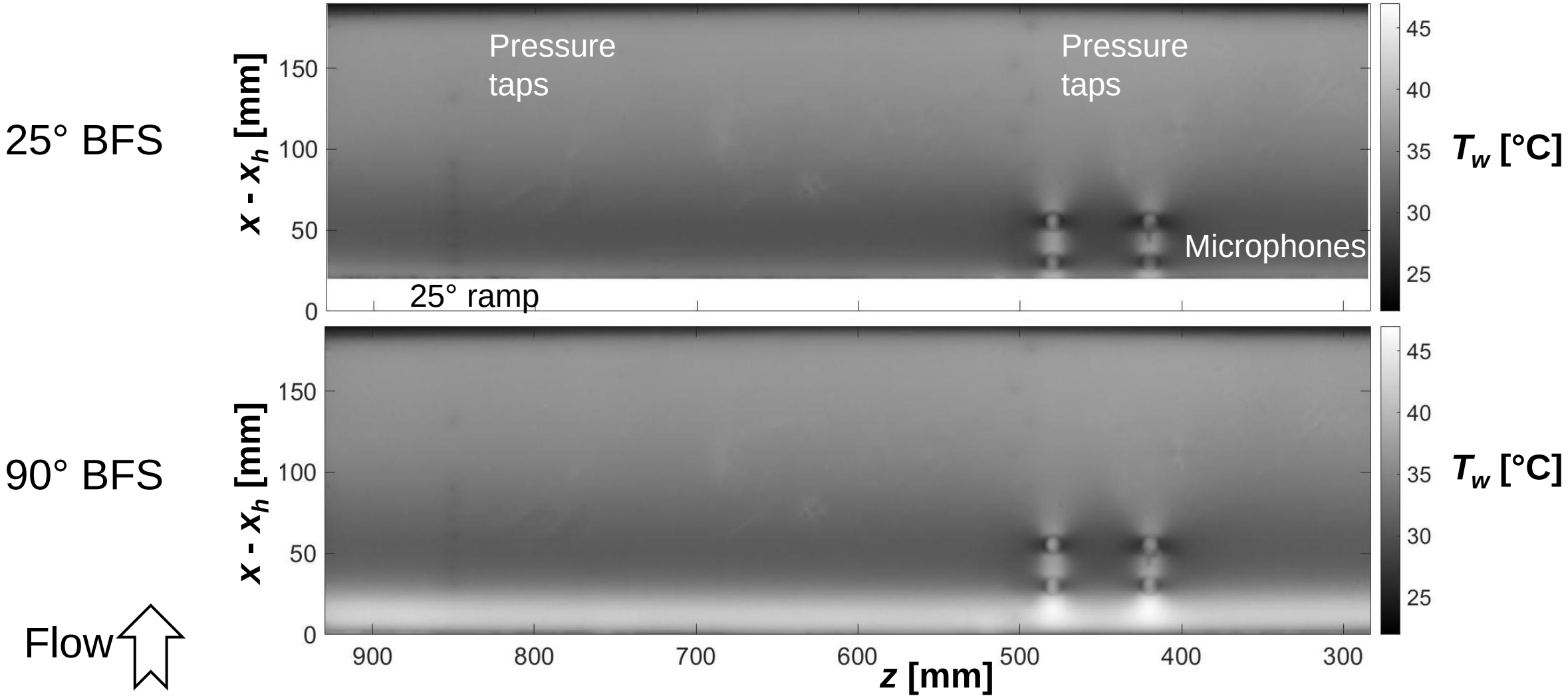






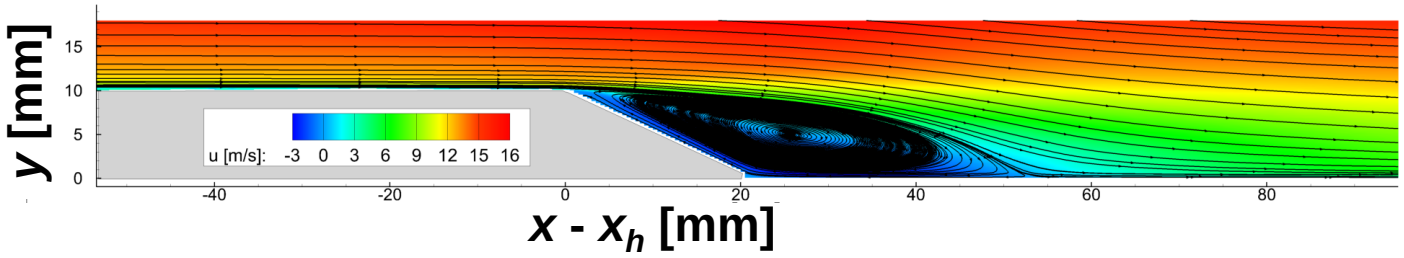
TSP data

- Time-averaged temperature distributions at U_∞ = 18.1 m/s
- Local thermal signatures due to the orifices for pressure taps and microphones

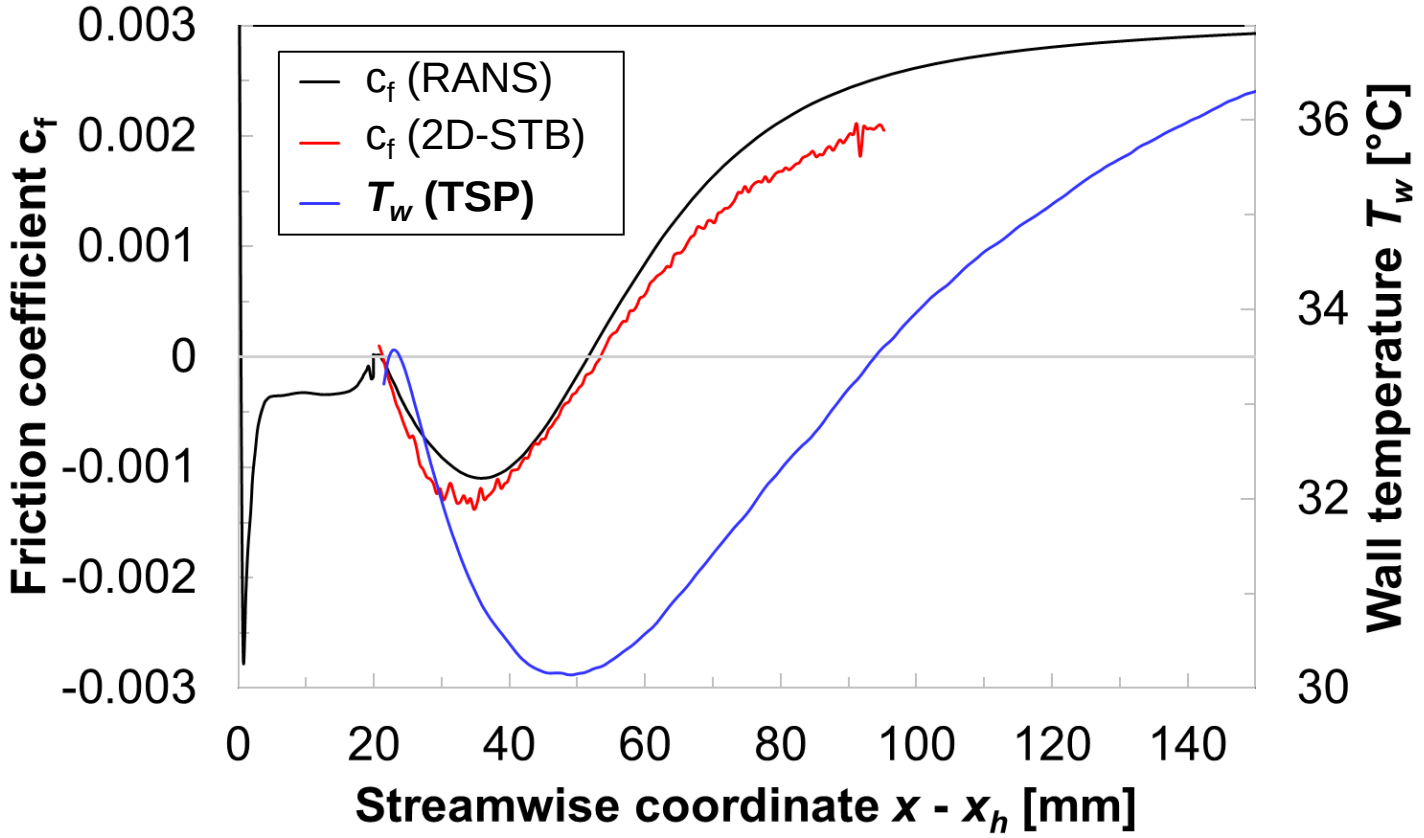


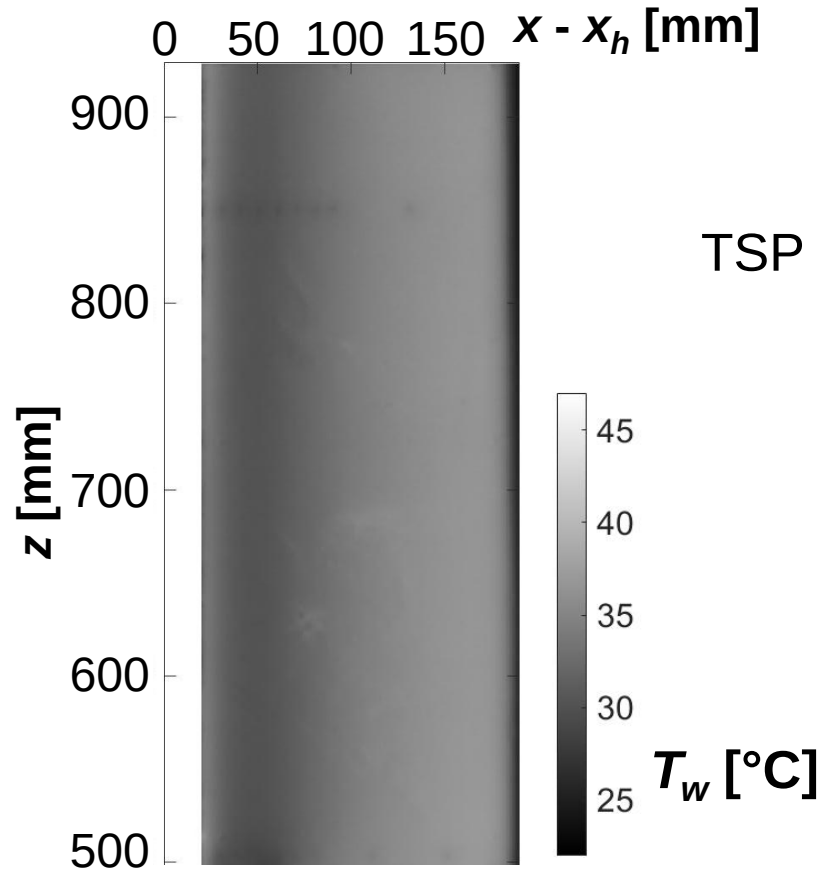
Preliminary results
Comparison of RANS, 2D-STB and TSP results

- 25° BFS configuration at U_∞ = 18.1 m/s



2D-STB





TSP

Summary

- Validation experiment on BFS-induced separation of a turbulent boundary layer designed and conducted in the DLR 1MG low-speed wind tunnel
- Promising preliminary agreement of measured and computed pressure distributions, velocity fields and skin-friction coefficients
- Minima and maxima of average temperature from TSP data appear to match flow reattachment and secondary separation detected in the 2D-STB data

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