der Bundeswehr
Universität München

Large Reynolds number boundary layer investigation with sophisticated high resolution imaging techniques

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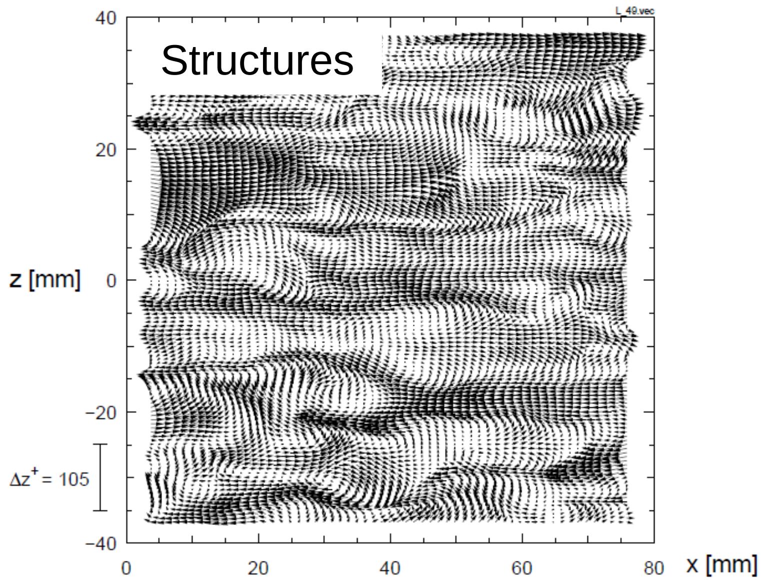
High Reynolds Number Boundary Layer Turbulence

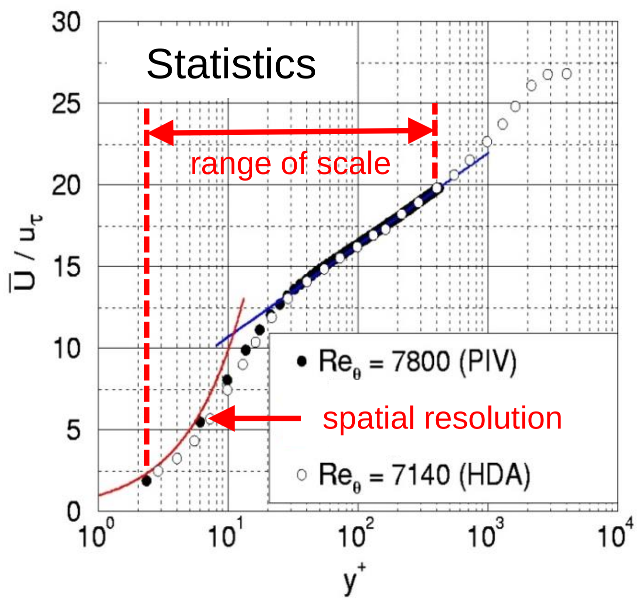
Integrating Descriptions of Statistical Structure, Scaling and Dynamical Evolution

November 20-22, 2013

University of New Hampshire

Motivation





Nature Vol. 270 3 November 1977

T.D. Dudderar, P.G. Simpkins

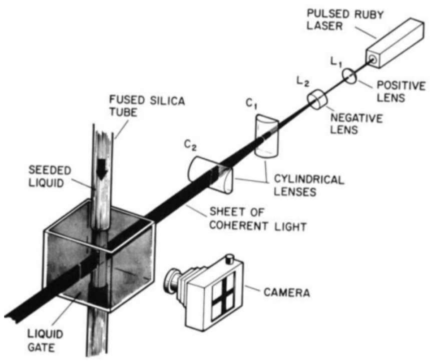
Laser speckle photography in a fluid medium → **PIV**

- \+ Non-inrusive
- \+ Multipoint technique
- \+ Fast data aquisition
- \+ Benefits from laser, camera & computer developments!

A TECHNIQUE for obtaining quantitative velocity data from hydrodynamic flow fields using laser speckle photography (LSP) has been developed and uses the scattered light from the interior of a suitably seeded liquid which is illuminated by a coherent beam from a pulsed ruby laser. The resulting speckle pattern can be photographed on high resolution film. A doubly exposed photograph of the correlated speckle patterns produced by fluid dynamic motion contains all the information necessary to describe the motion throughout a selected plane. When the speckle photographs are optically interrogated distinct fringe patterns are produced whose geometries are related to the velocity field. Here we describe how a Poiseuille flow was used to demonstrate this novel technique. Doubly exposed speckle photographs and typical fringe patterns illustrating the velocity distribution are given, analysed and compared with the classical theory.

The LSP technique has been used since 1969 almost exclusively for various applications to surface metrology[1-3]. Barker and Fourney[4] have extended the method to measure displacements in the interior of a transparent solid by recording side-scattered light from an illuminated domain. With lasers of conventional power such recordings require very long exposures. Consequently, the few applications reported so far have examined only imposed static strains. The basic difference between that work and the present application to fluids is that the latter is truly dynamic involving moving liquids rather than static solids.

The extension of side-scattering speckle techniques to fluid dynamic situations has been achieved by using a double pulsed Q-switched ruby laser and a suitably seeded medium. The experimental arrangement used to record speckle photographs of the flow field is shown in Fig. 1. The beam from a ruby laser, which



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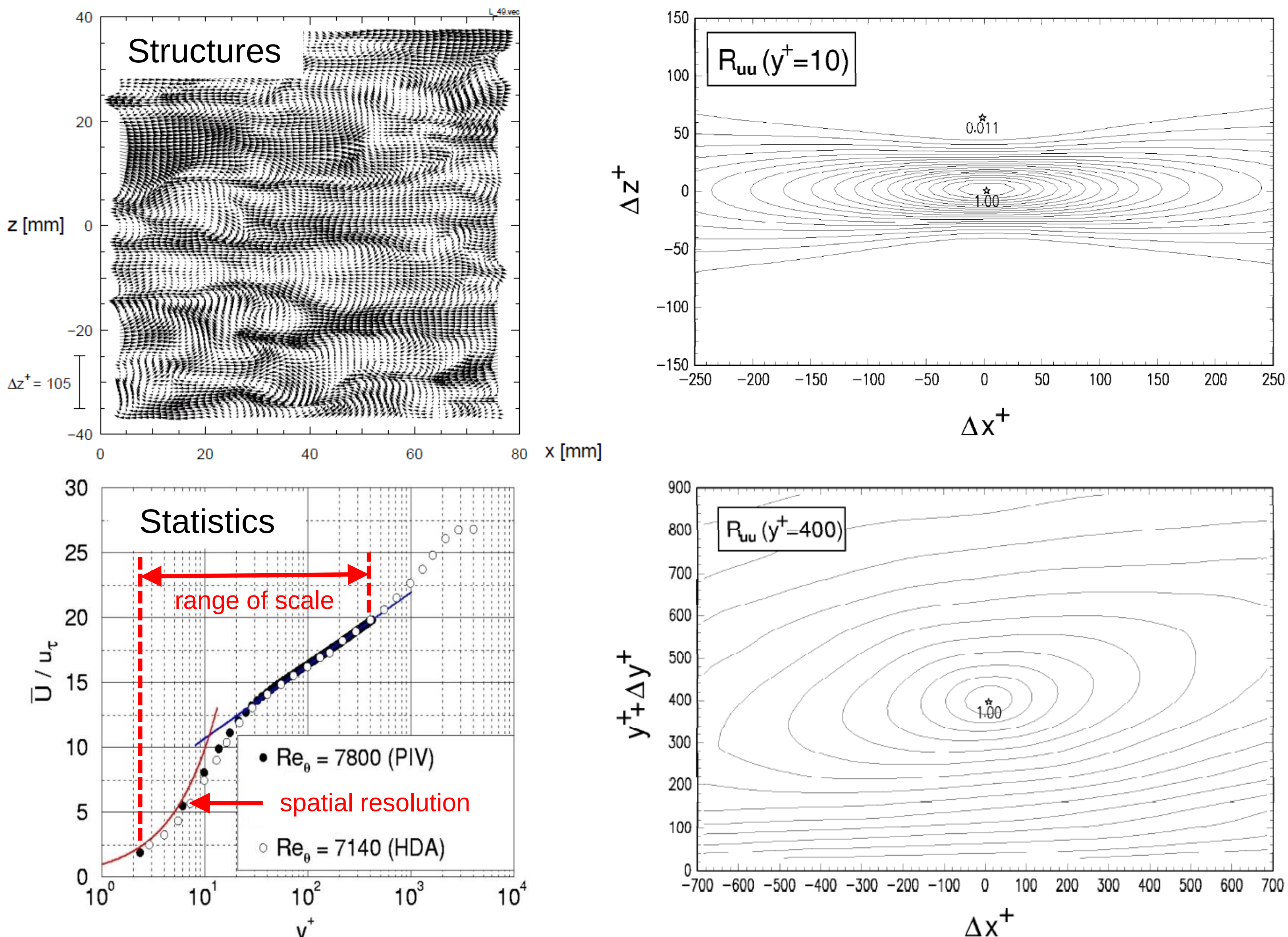
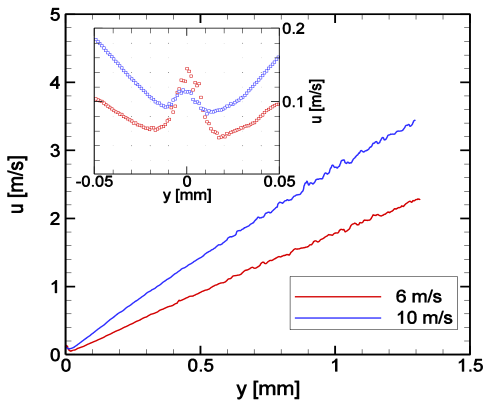

Structures
z [mm]
x [mm]
Δz+ = 105
40
20
0
−20
−40
0
20
40
60
80
R_{uu} (y^+=10)
0.011
1.00
Δz+
Δx+
Statistics
range of scale
spatial resolution
● Re_θ = 7800 (PIV)
○ Re_θ = 7140 (HDA)
$\bar{U} / u_\tau$
y+
R_{uu} (y^+=400)
1.00
y+ + Δy+
Δx+

Major developments

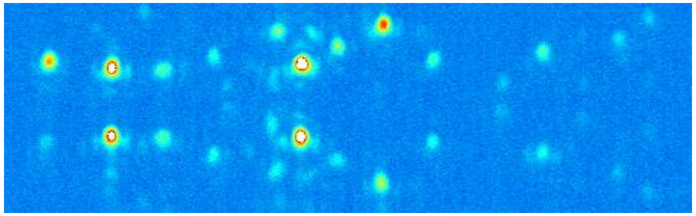
2000 Meinhart et al. *A PIV algorithm for estimating* ***time-averaged*** *velocity fields*. J Fluids Eng 122, 285 – 289

2004 Westerweel et al. ***Single-pixel*** *resolution ensemble correlation for* ***micro-PIV*** *applications*. Exp. Fluids 37, 375 – 384

2006 Kähler et al. *Wall-shear-stress and near-wall* ***turbulence*** *measurements up to single pixel resolution by means of LD micro-PIV*. Exp. Fluids 41, 327 –341



Resolution: 0.00071 mm → 0.028 wall units!



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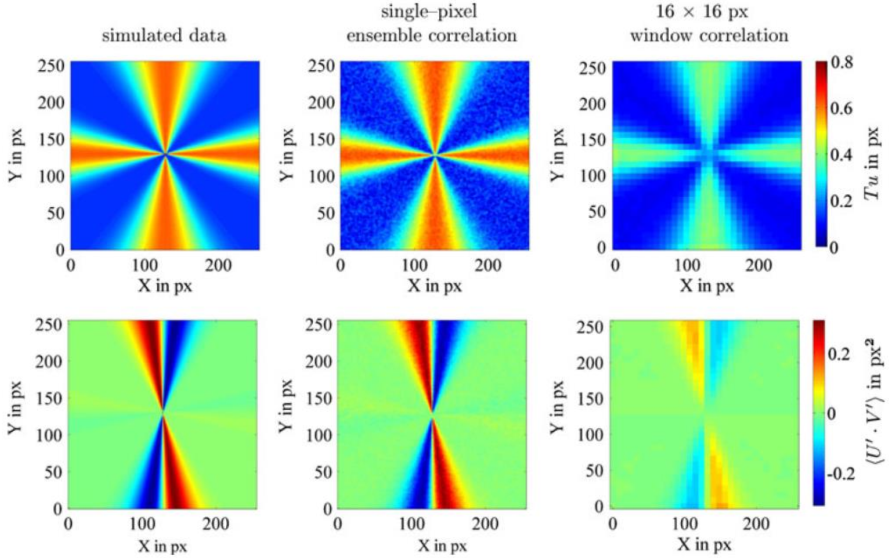

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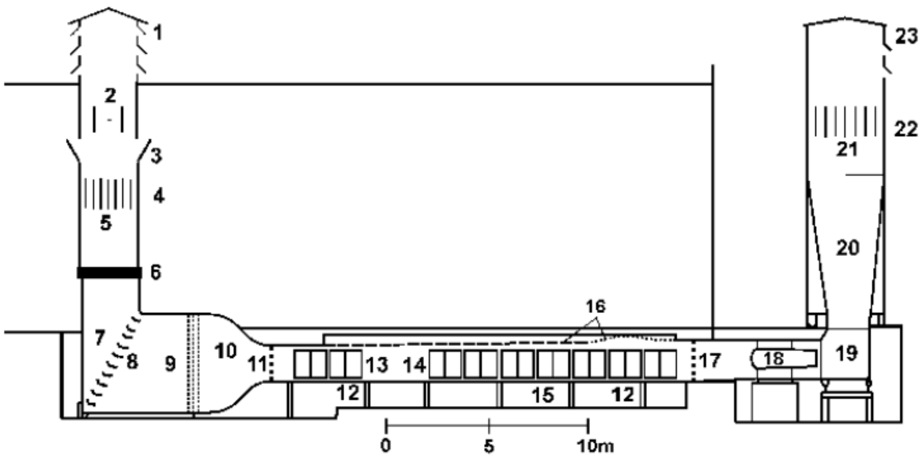
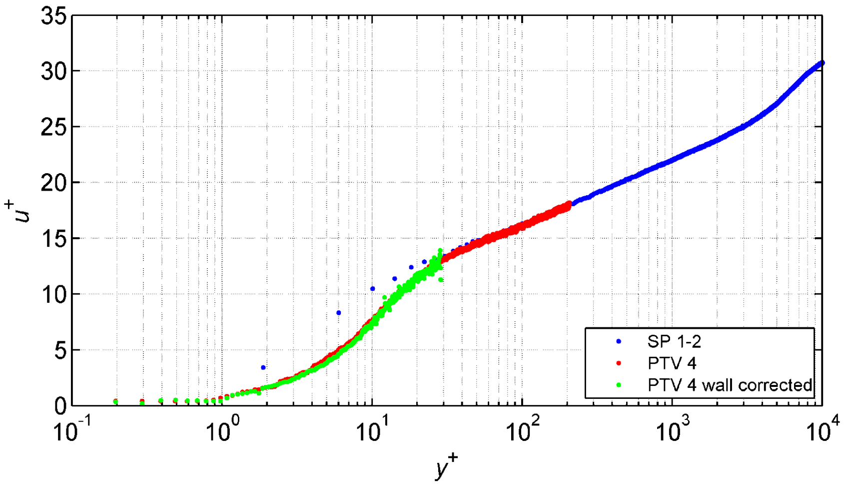
2012 Kähler et al. *On the* ***resolution limit*** *of digital Particle Image Velocimetry*. Exp. Fluids 52, 1629 – 1639

2012 Kähler et al. *On the* ***uncertainty*** *of digital PIV and PTV* ***near walls***. Exp. Fluids 52, 1641 – 1656

2013 Cierpka et al. ***Parallax correction*** *for precise near-wall flow investigations using particle imaging.* Applied Optics, Vol. 52, 2923 – 2931

Low speed investigations





Re in $10^6\,m^{-1}$	u_∞ in m/s	δ_{99} in mm	u_τ in m/s	τ_w in N/m²
0.75	11.06 ± 0.02	535 ± 3	0.34 ± 0.01	0.14 ± 0.01
1.50	21.13 ± 0.03	457 ± 5	0.67 ± 0.02	0.52 ± 0.02
2.04	30.30 ± 0.05	455 ± 4	0.93 ± 0.03	1.01 ± 0.04

Conclusions

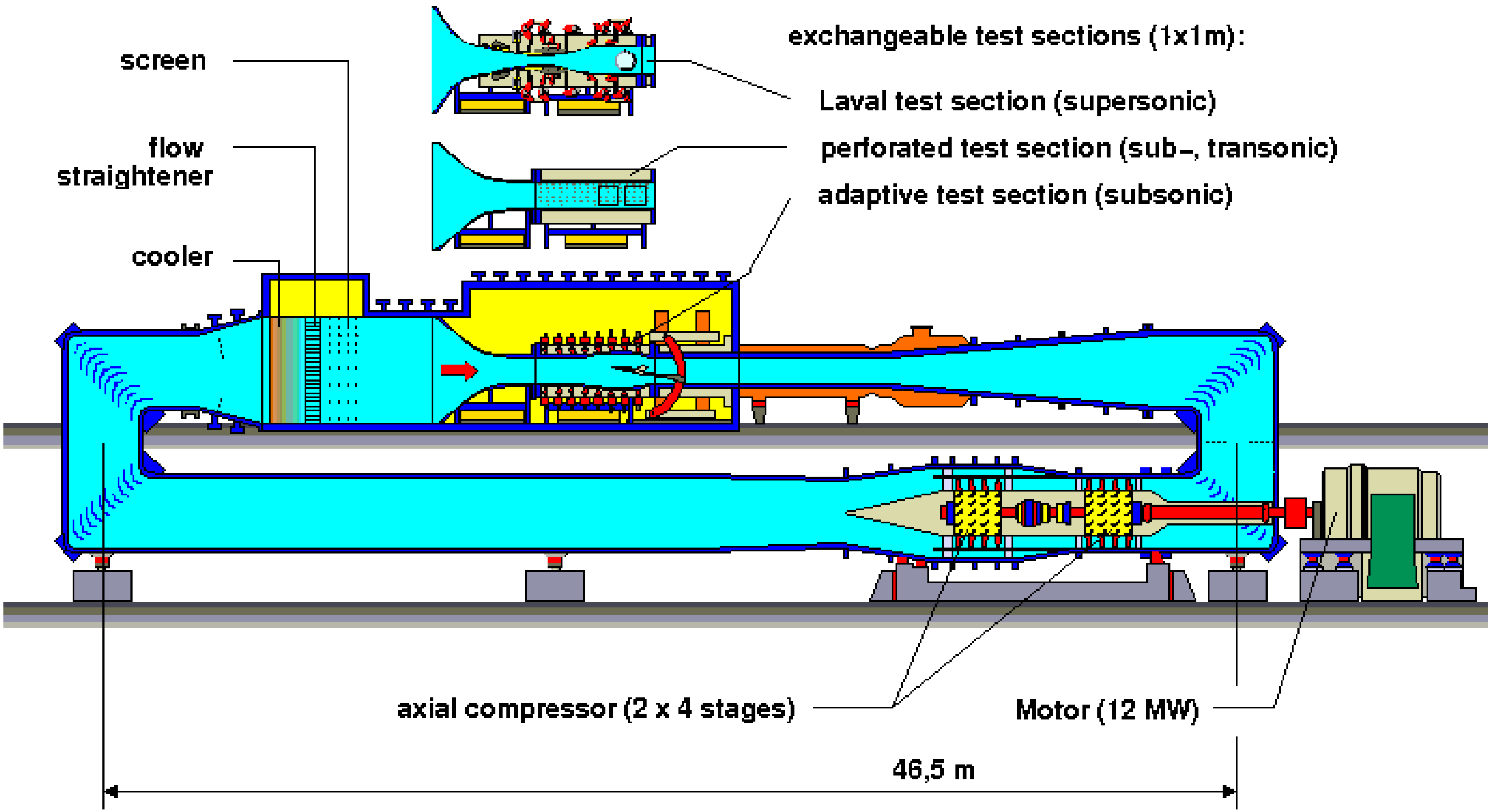
High resolution measurements of statistical quantities like **average velocities**, **Reynolds stresses**, **higher order moments**, **pdf‘s** are possible with PIV / PTV **at low speed**.

To reach large Reynolds numbers, long test sections are required.

- large scale flow structures cannot be resolves because of **large δ**.
- promotes uncertainties in **initial** (pumping,…) / **boundary** conditions (vibrations, …)
- side wall and **blockage** effects may alter flow.

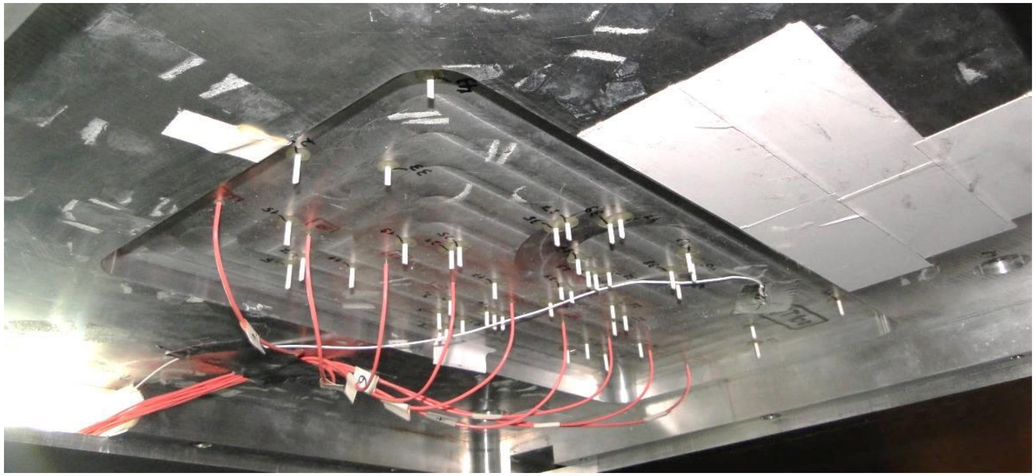
High resolution measurements on short models at high flow velocity are desired!

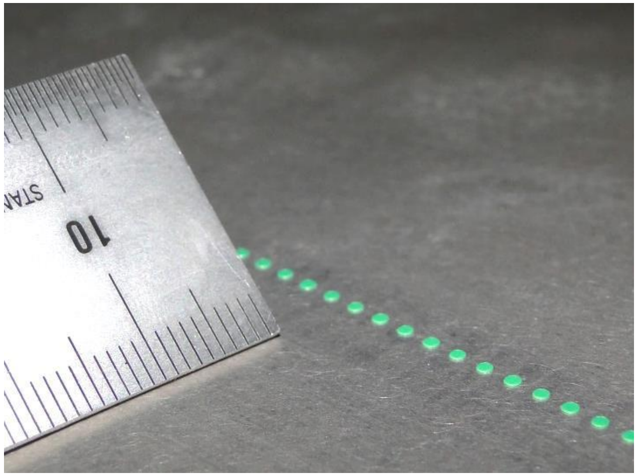
Transonic Windtunnel Göttingen TWG



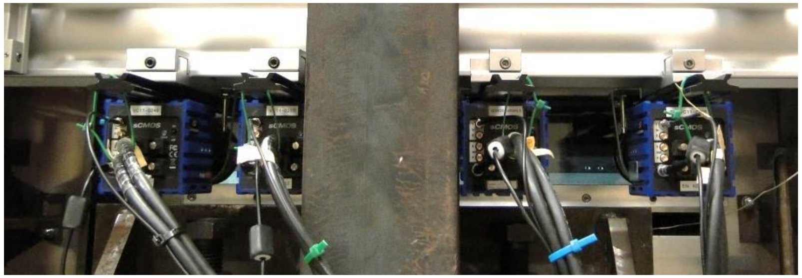
Transonic Windtunnel Göttingen TWG

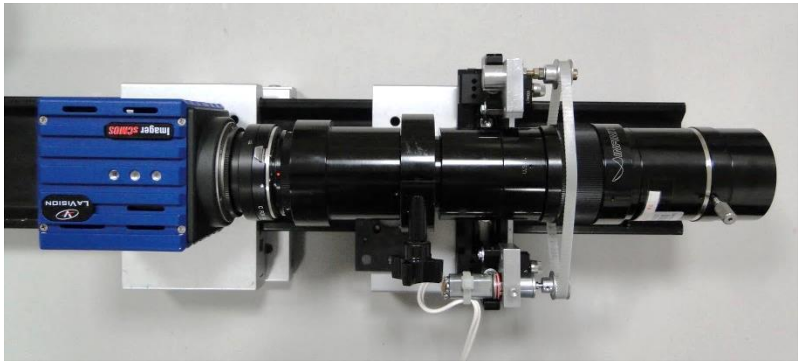
Model

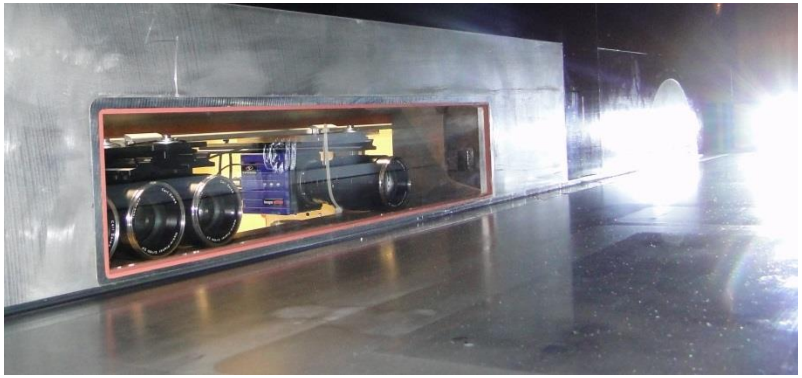


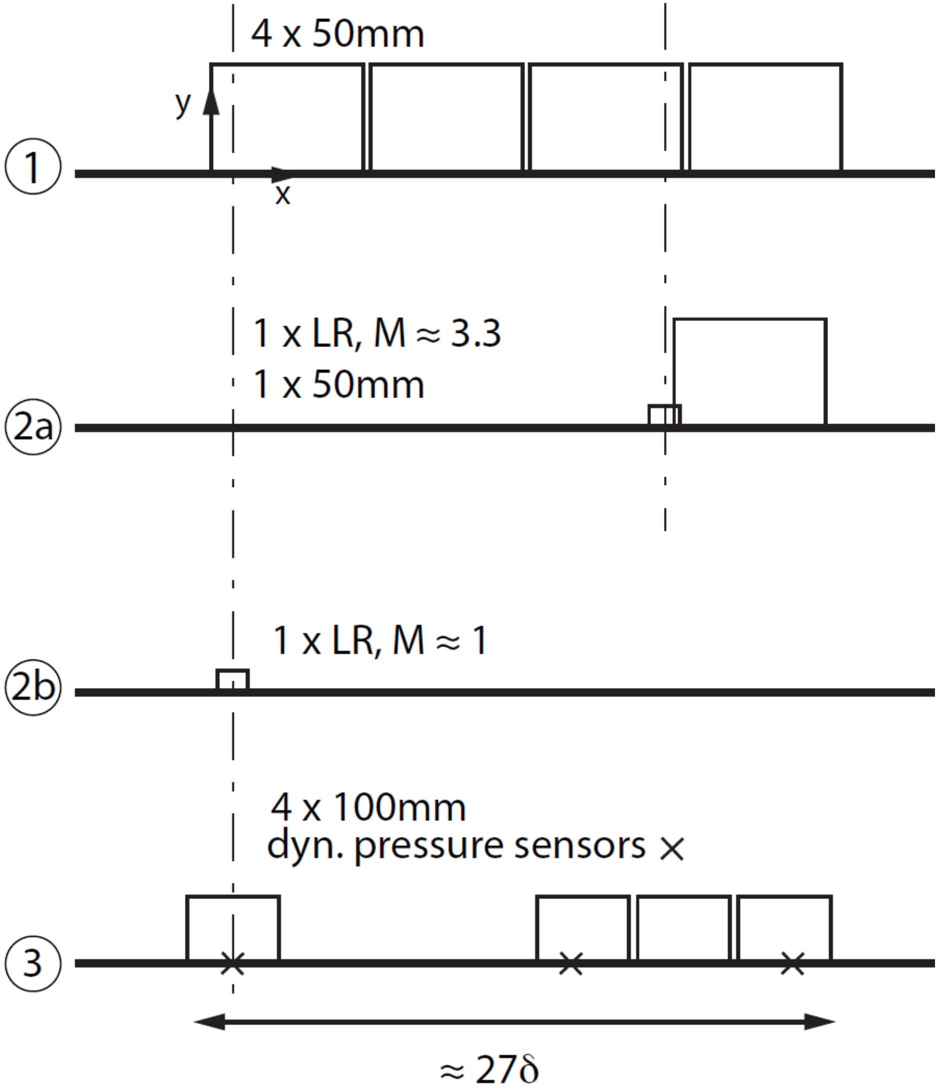


PIV configuration

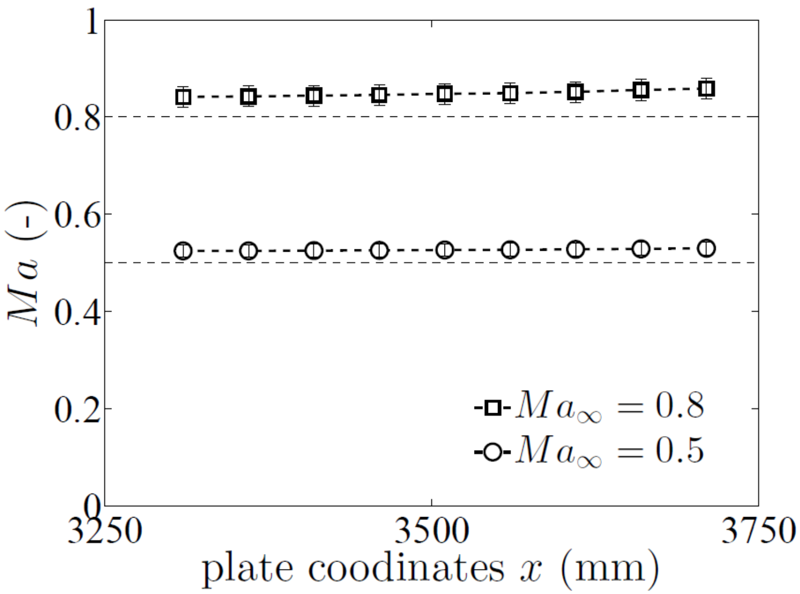


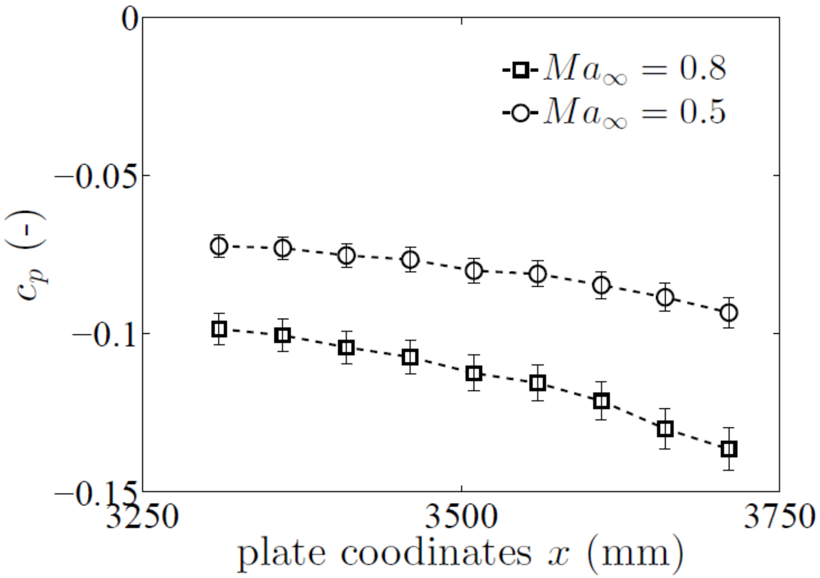






Parameter

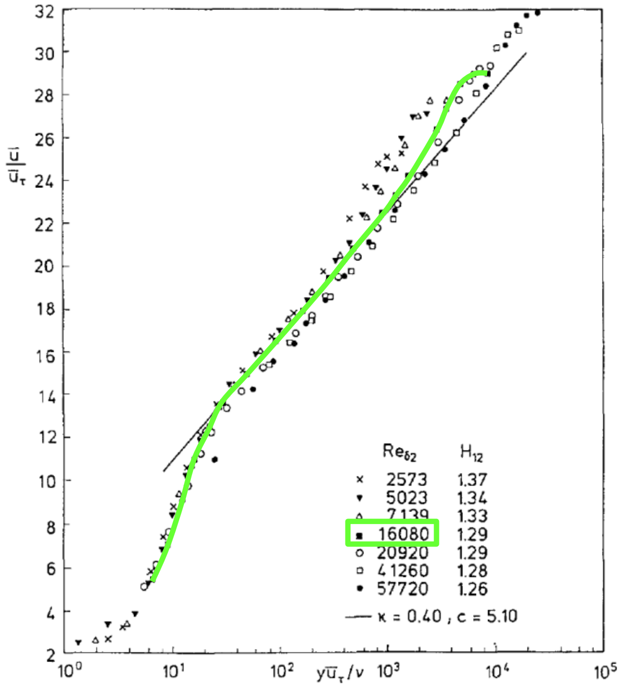


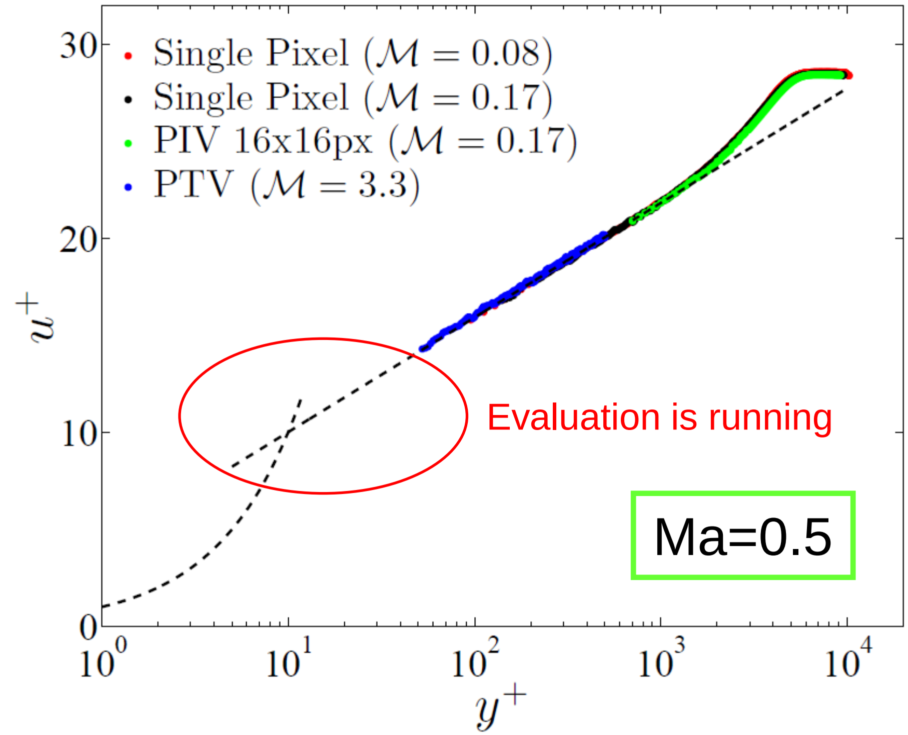


Ma	p_0 (kPa)	Re_{tau}	Re_{theta}	U_o (m/s)	u_{tau} (m/s)	$delta_{99}$ (mm)	theta (mm)	$1/y^+$ (µm)
0.8	50	7,800	23,000	270.6	9.26	27.2	3.54	3.48
0.5	50	5,350	15,700	171.0	6.00	28.1	3.81	5.25
0.5	100	-	-	-	-	-	-	-

Fernholz and Finley

Prog. Aerospace Sci. Vol. 32, pp. 245-311, 1996





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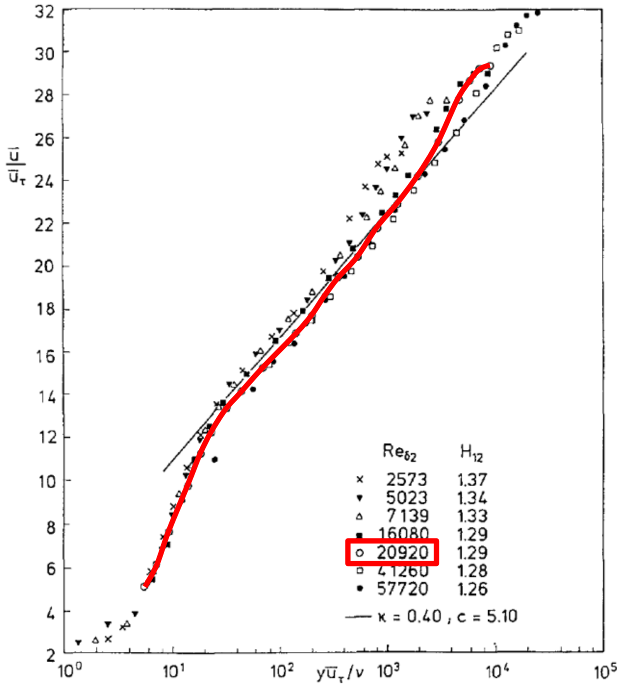

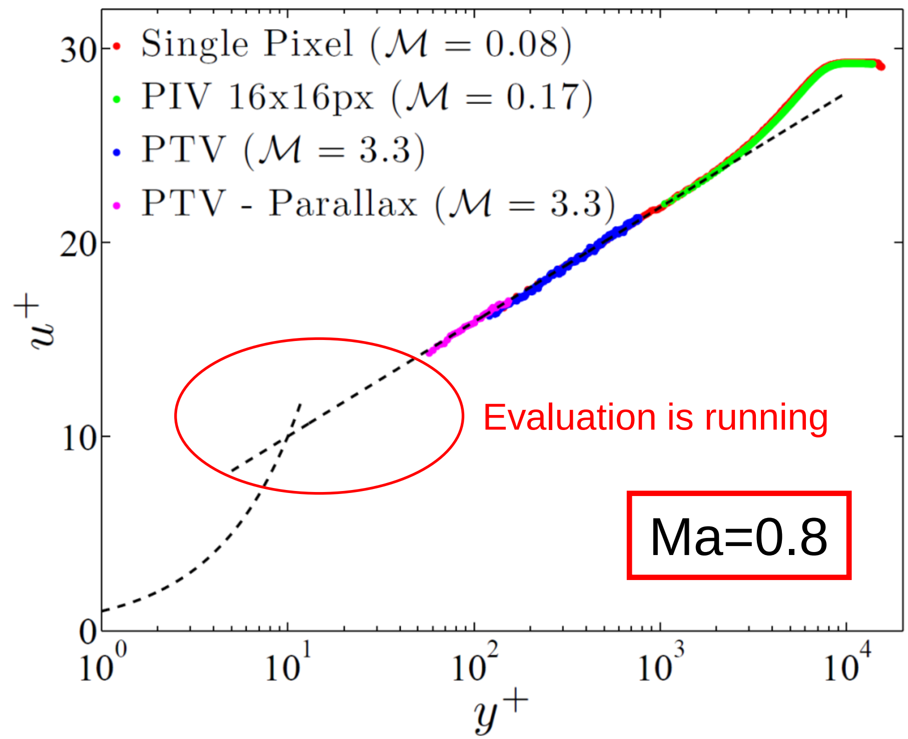

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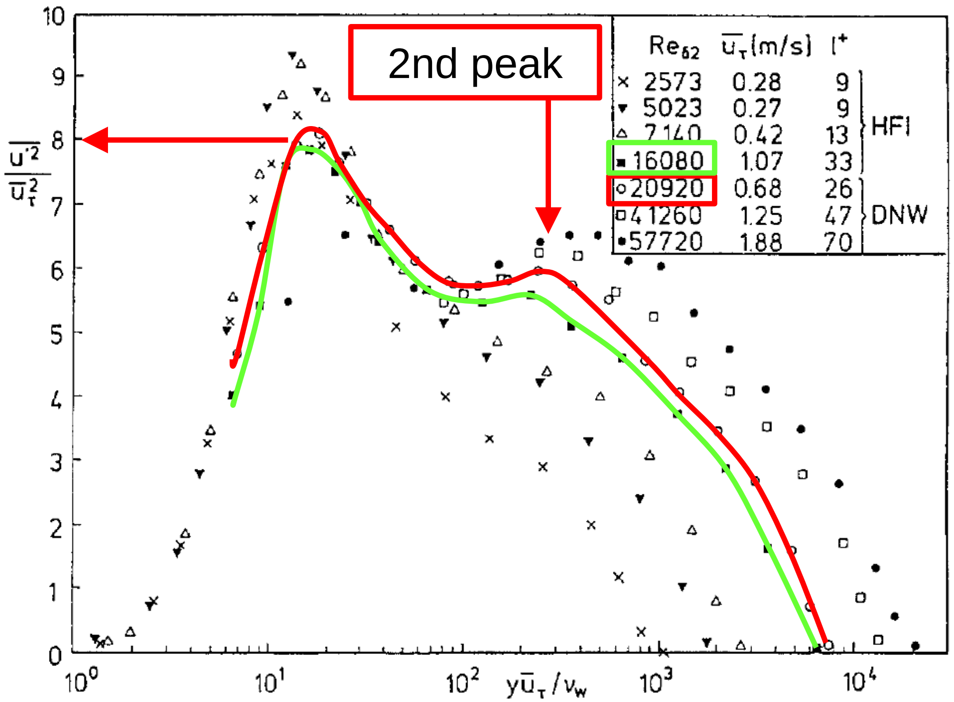

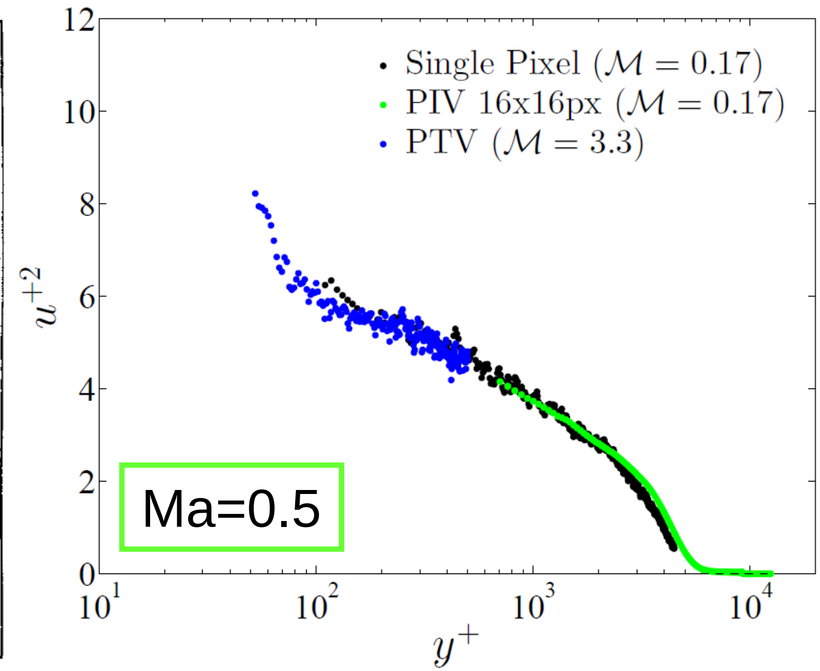

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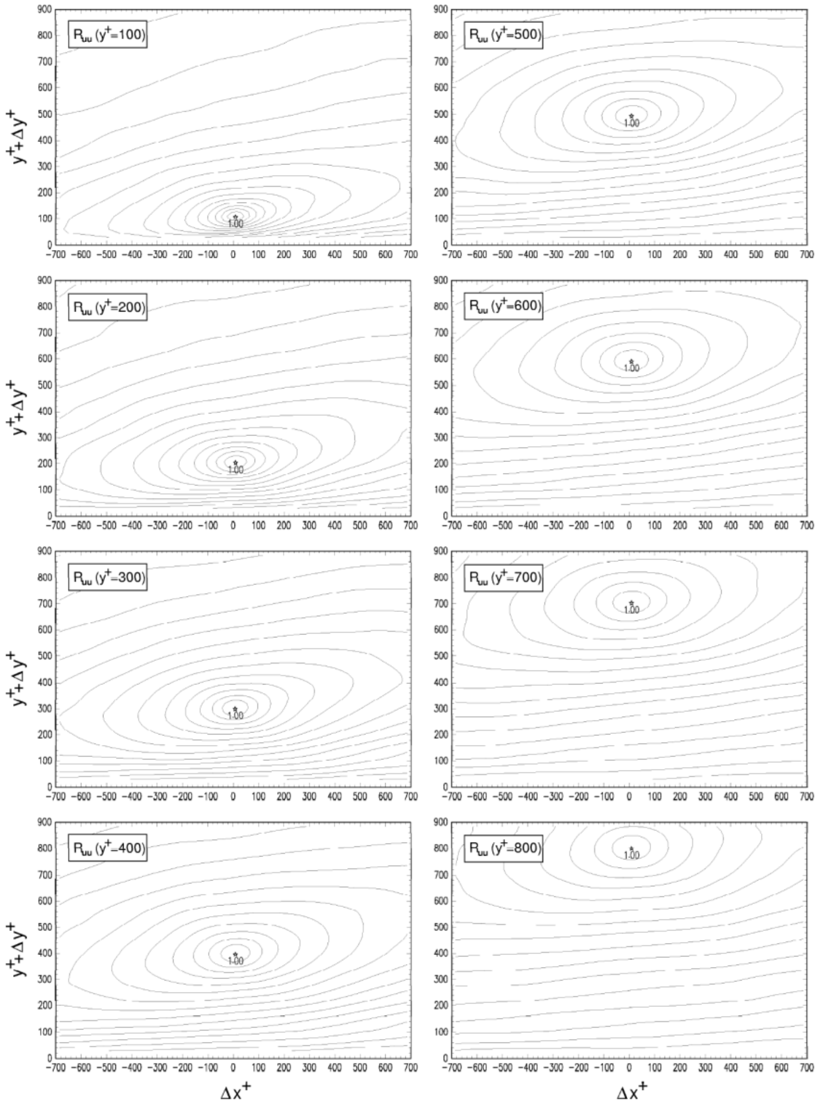
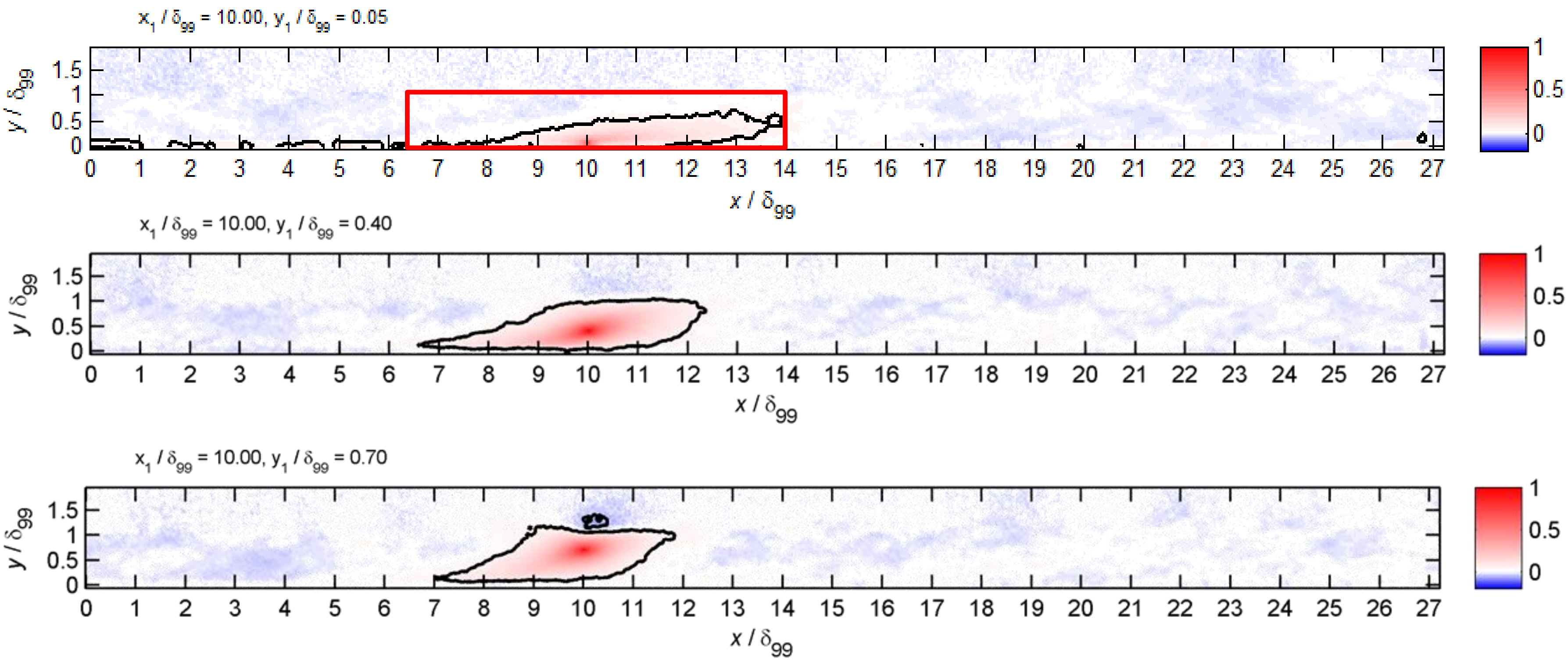
Two-point correlation Ma=0.02



Kähler, *The significance of coherent flow structures for the turbulent mixing in wall-bounded flows*. DLR-FB-24, 2004

http://ediss.uni-goettingen.de/bitstream/handle/11858/00-1735-0000-0006-B4C8-8/kaehler.pdf?sequence=1

Two-point correlation
Ma=0.8

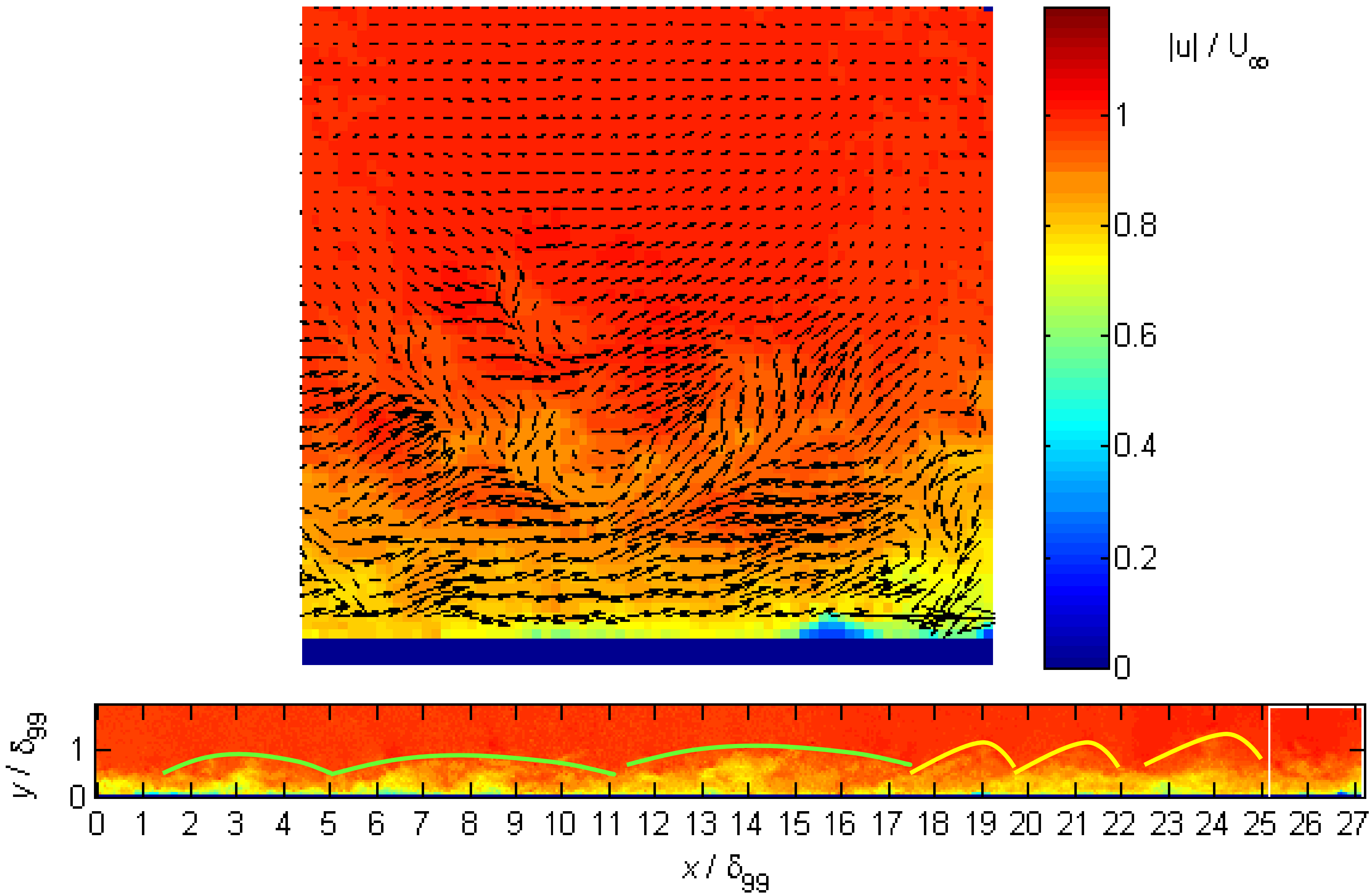


R_{uu} correlation arround 6δ in x direction

no periodicity of R_{uu} in x direction

large structures are uncorrelated due to meandering

Instantaneous flow field
Ma=0.8



Conclusions

Large Reynolds number investigations at high Ma are possible with sophisticate PIV / PTV recording and evaluation techniques.

- Side wall and blockage effects can be neglected.
- Uncertainties in the initial and boundary conditions can be reduced.

Investigation at Ma=0.5 and 0.8 indicate:

- good statistical agreement with results of Fernholz and Finley in DNW.
- weak second peak is visible as expected
- R_{uu} correlates arround 7δ in x direction
- no periodicity of R_{uu} in x direction
- superstructures are uncorrelated in x
- decorrelation associated with meandering of large structures.