



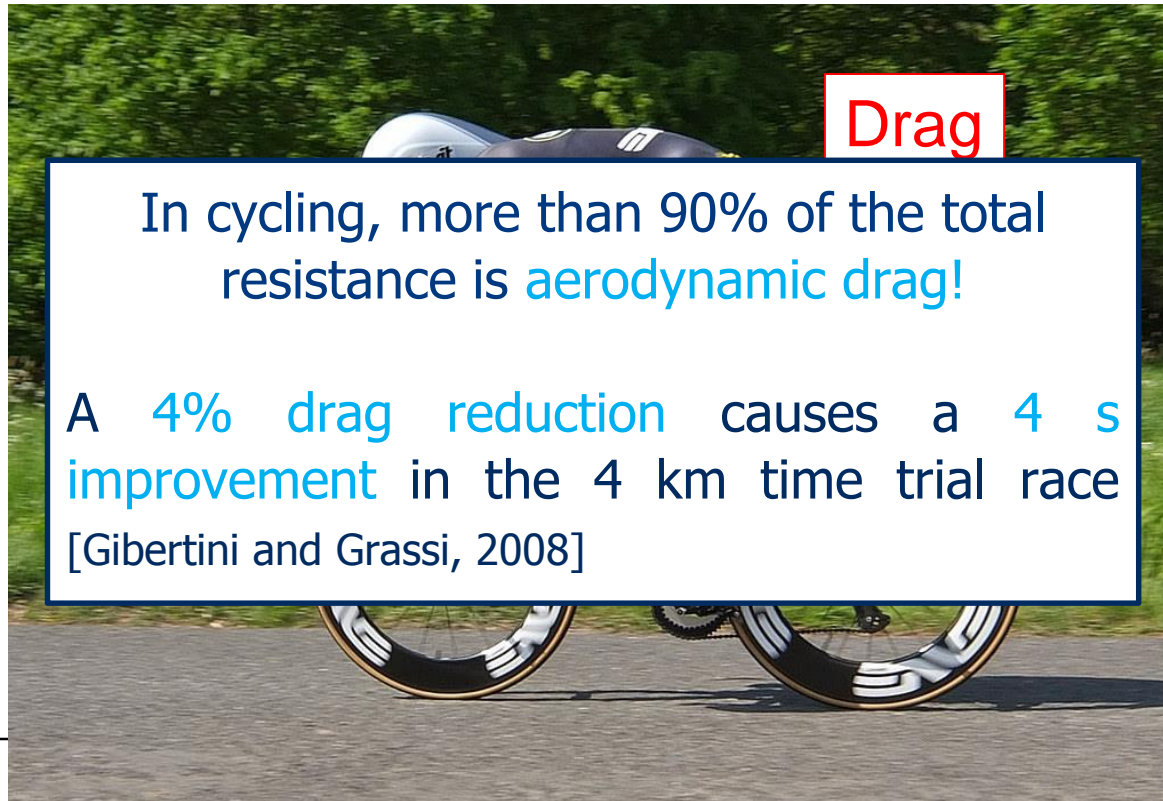
A quantitative flow visualization technique for on-site sport aerodynamics optimization

Aerodynamics

Definition

Study of the dynamics of air, especially when interacting with solid objects

When a solid body is moving through a fluid **aerodynamic forces (lift and drag)** and moments are produced



In cycling, more than 90% of the total resistance is **aerodynamic drag!**

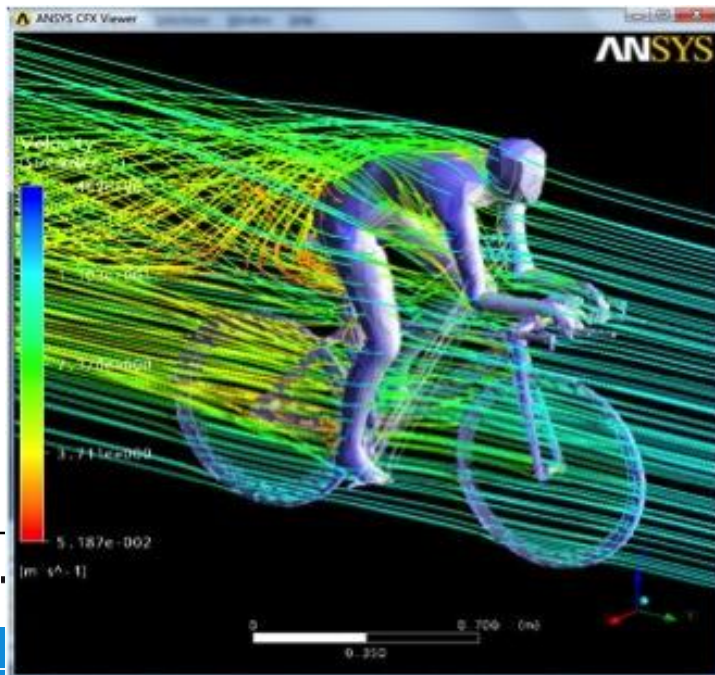
A **4% drag reduction** causes a **4 s improvement** in the 4 km time trial race
[Gibertini and Grassi, 2008]

Aerodynamic investigation approaches

Numerical investigation

(computational fluid dynamics, CFD)

Numerical solution of the flow equations
(Navier-Stokes equations)



Experimental investigation

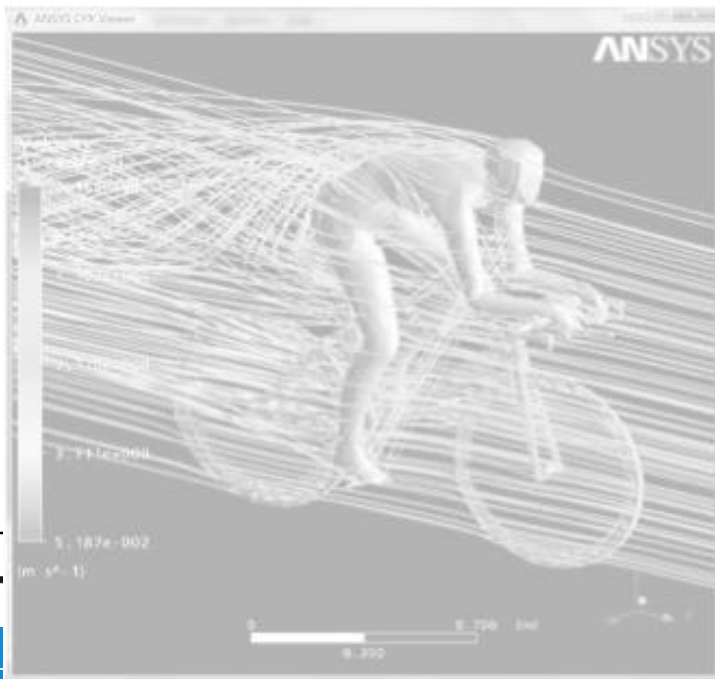
Measurement in wind tunnel to reproduce the
flow conditions



Aerodynamic investigation approaches

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(computational fluid dynamics, CFD)

Numerical solution of the equations of motion
(Navier-Stokes equations)



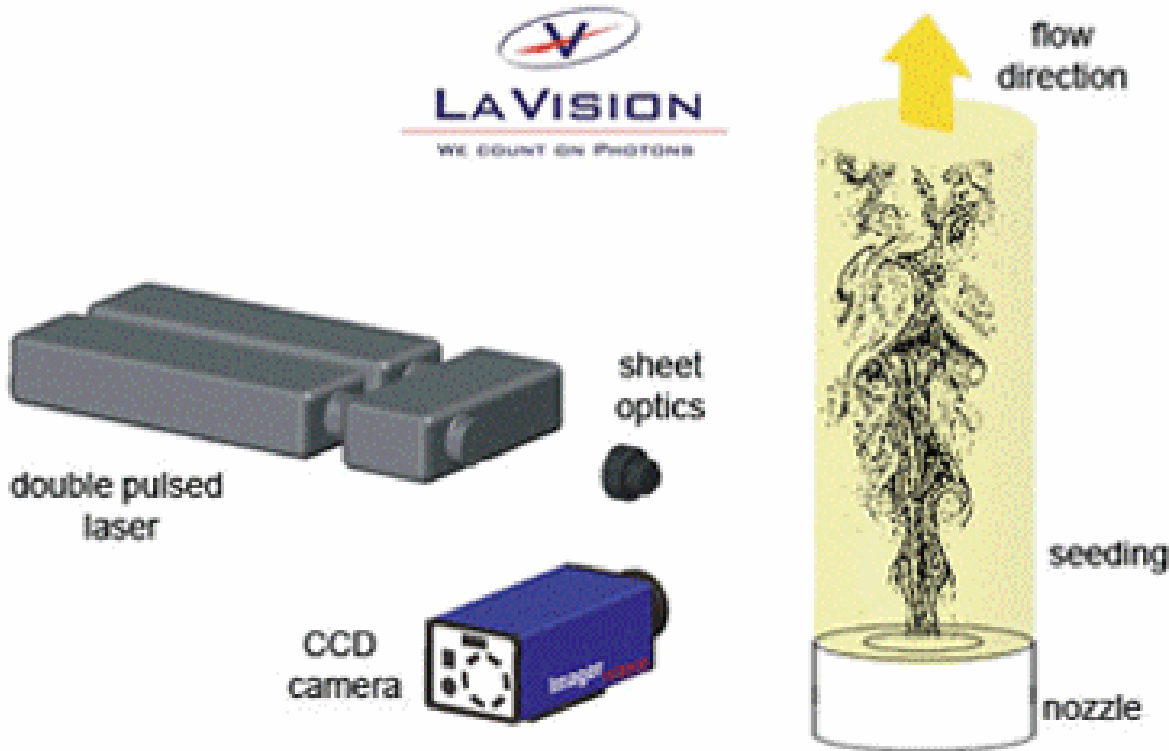
Experimental investigation

Measurement in wind tunnel to reproduce the
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Particle Image Velocimetry (PIV)

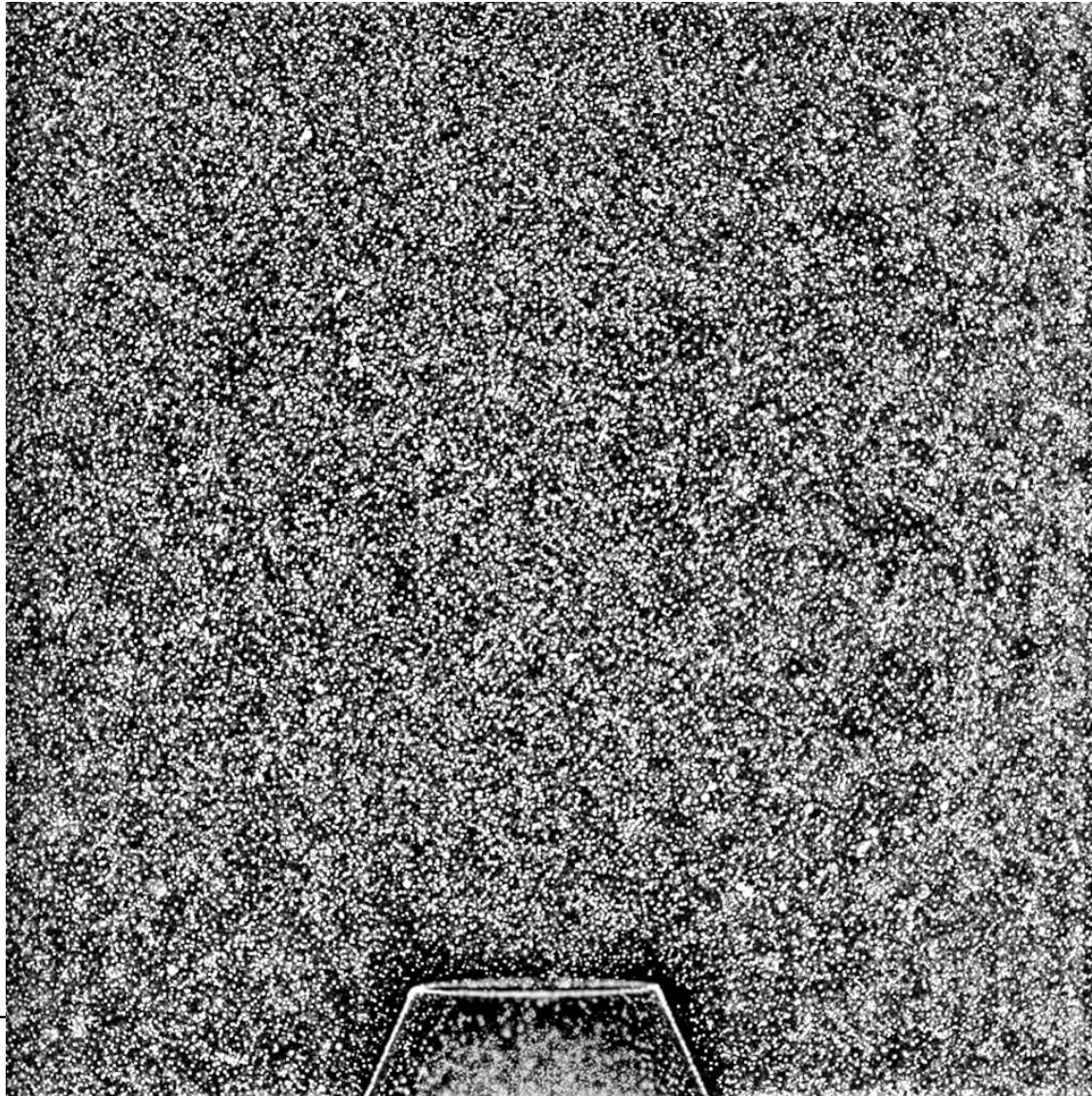
Working principle



- Small particles in the flow
- Illumination provided by laser
- Images recorded by a camera
- Flow velocity extracted from the particles displacement

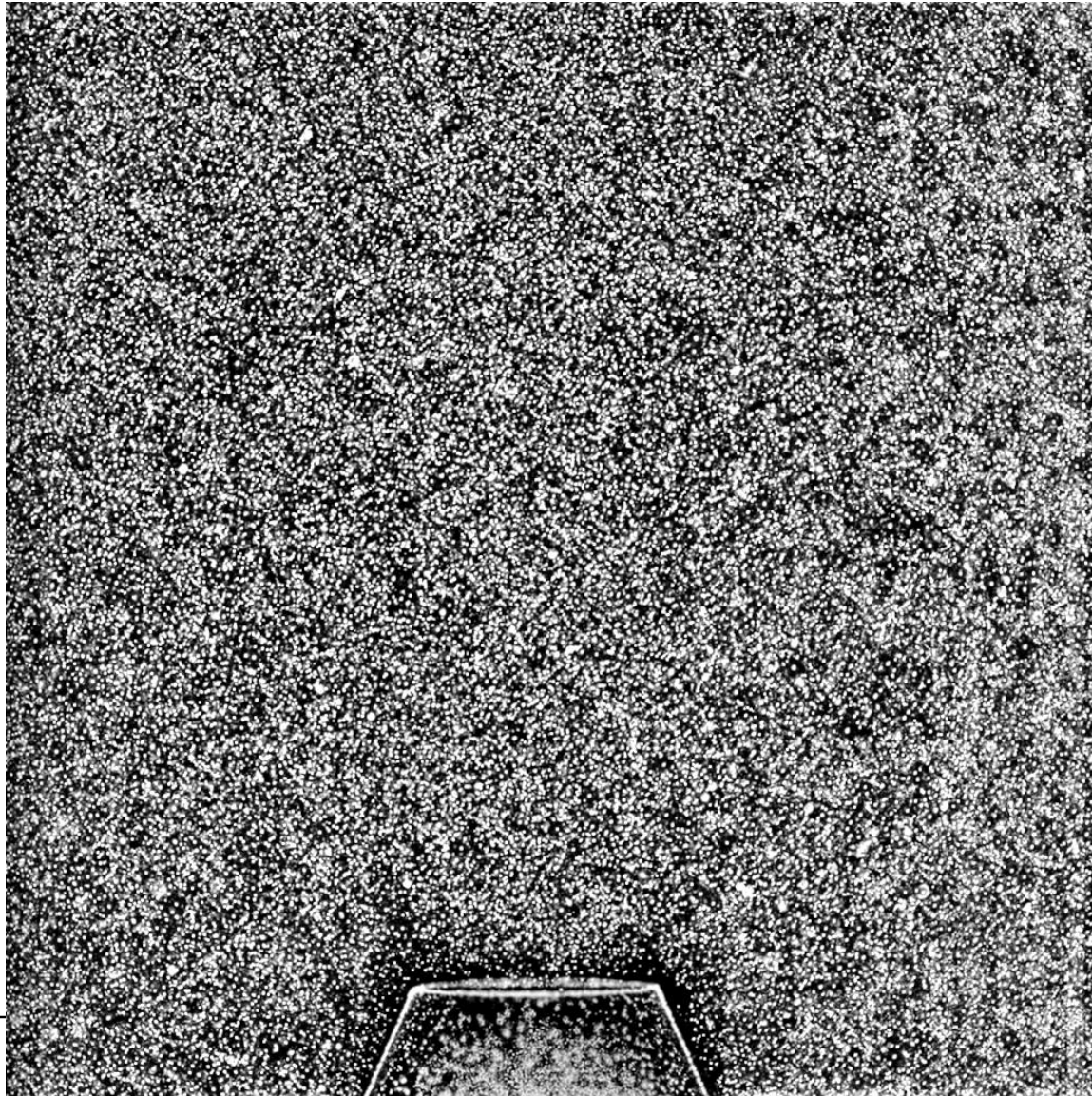
Example of PIV: Jet flow

Image 1

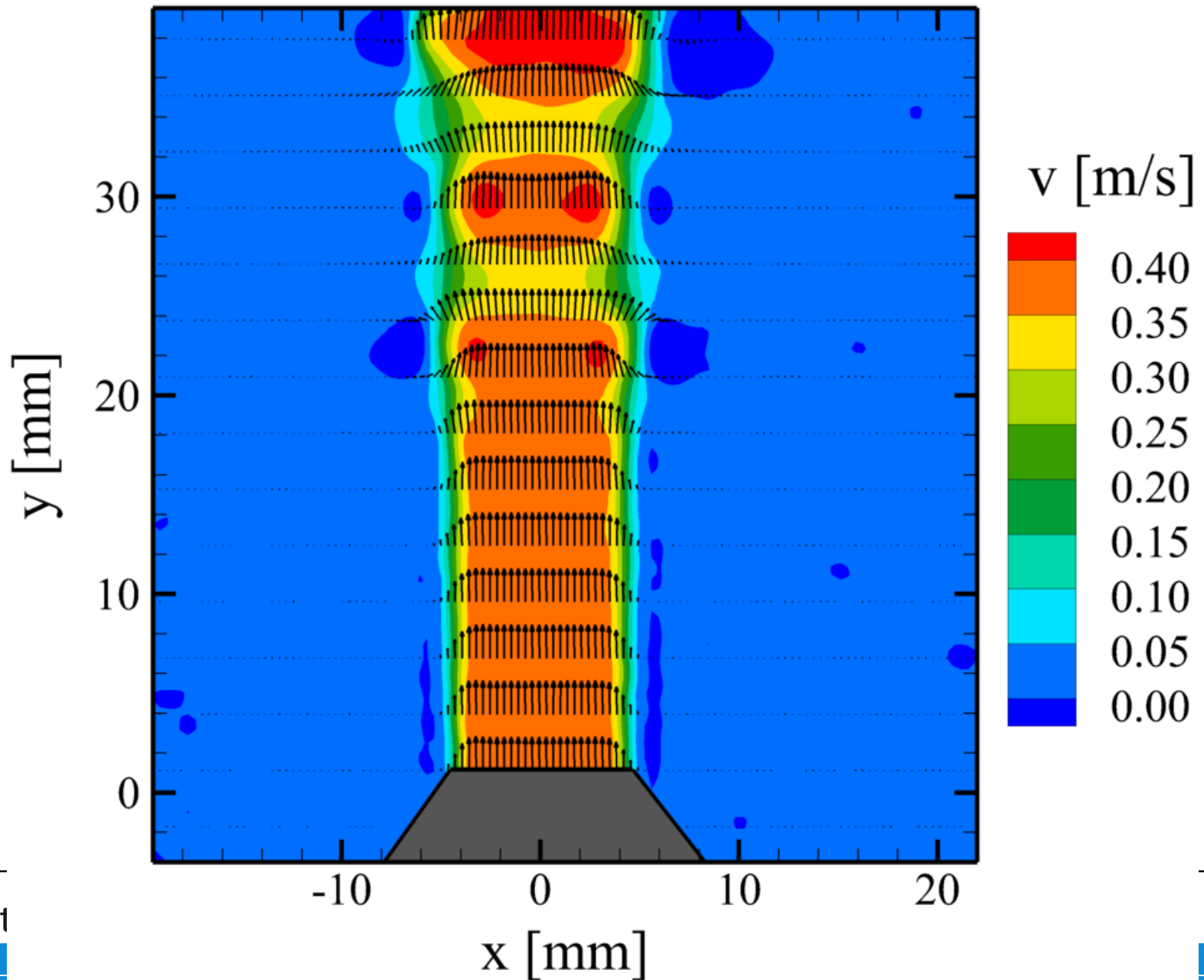


Example of PIV: Jet flow

Image 2



Axial velocity component



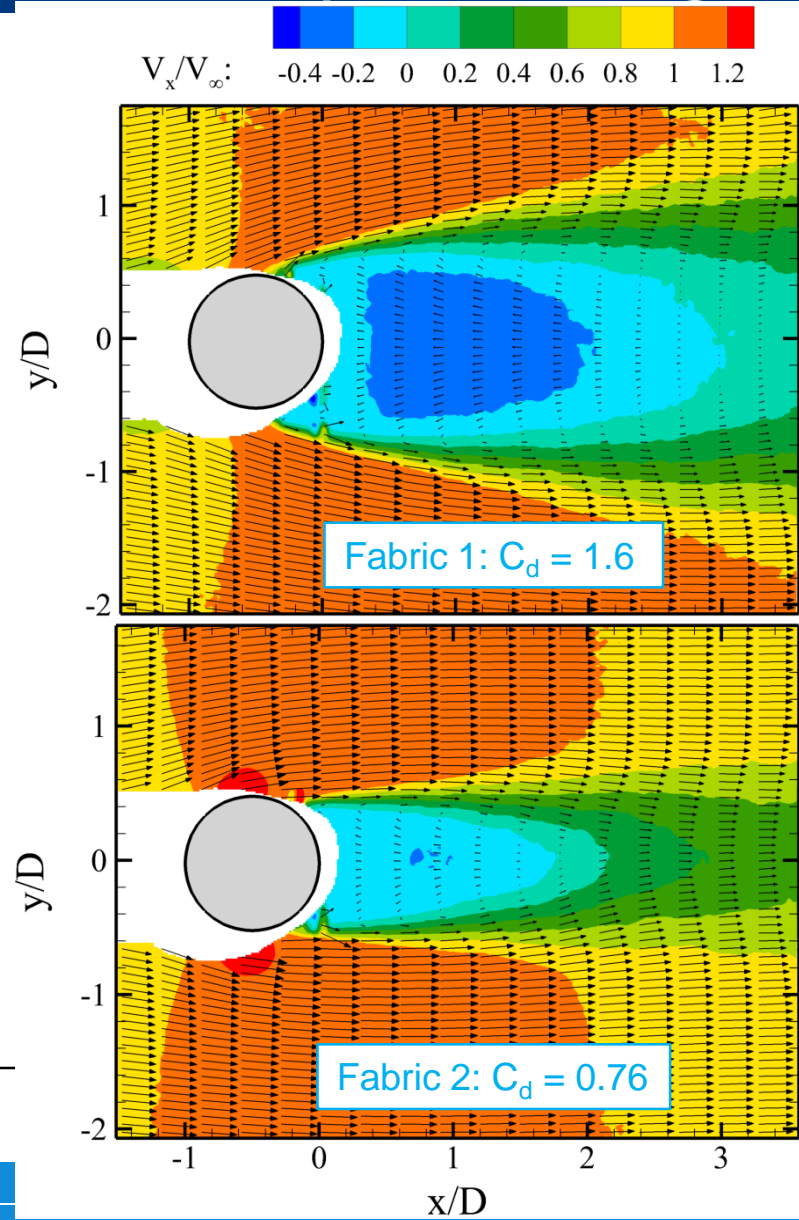
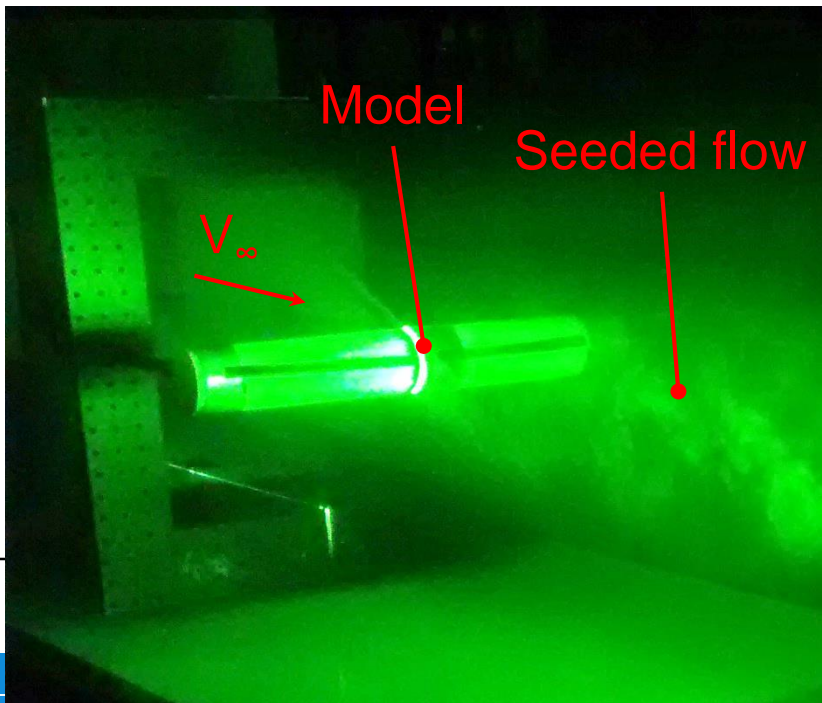
PIV APPLICATION

[Experiments conducted by W. Terra]

Effect of fabric roughness on aerodynamic drag

Experimental parameters

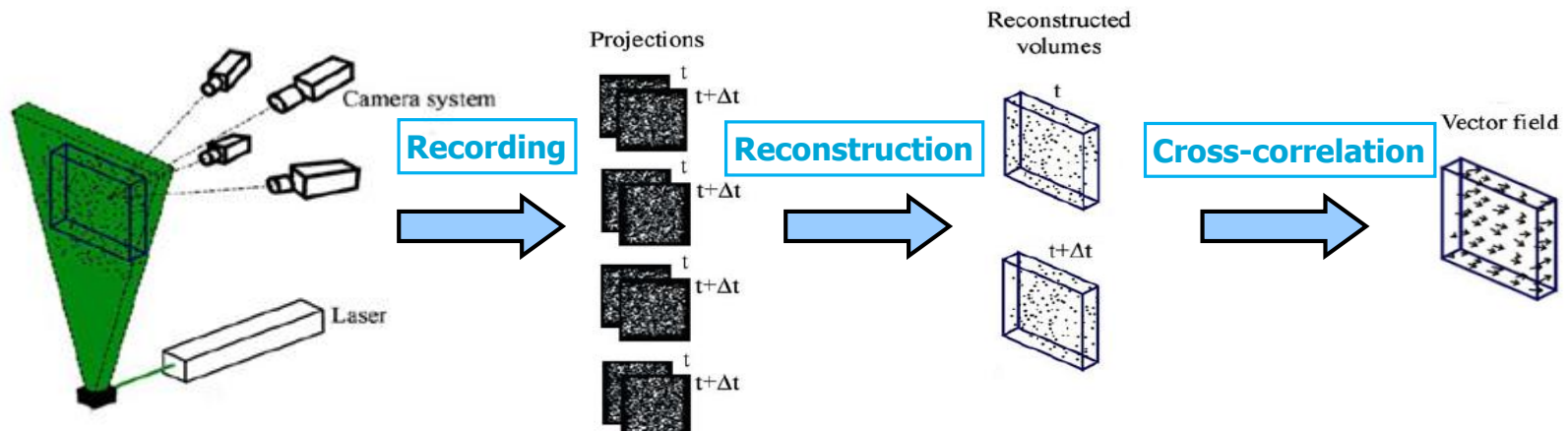
Cylinder diameter D	7 cm
Free-stream velocity V_∞	25.6 m/s
Reynolds number Re_D	1.2×10^5
Measurement domain	$356 \times 269 \text{ mm}^2$
Spatial resolution	0.97 vector/mm



Tomographic PIV

Velocity field in a 3D volume

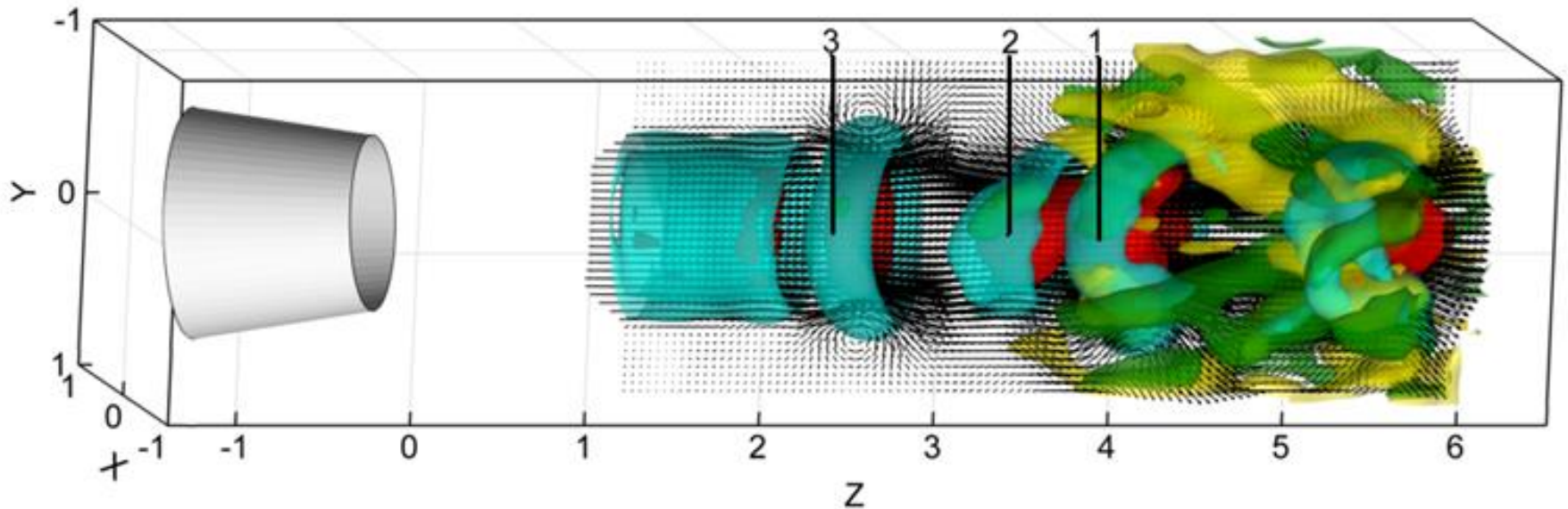
- 3 or more cameras required
- Additional step: reconstruction of the volume
- Output: $u(x,y,z)$, $v(x,y,z)$ and $w(x,y,z)$: 3 velocity components in a 3D domain



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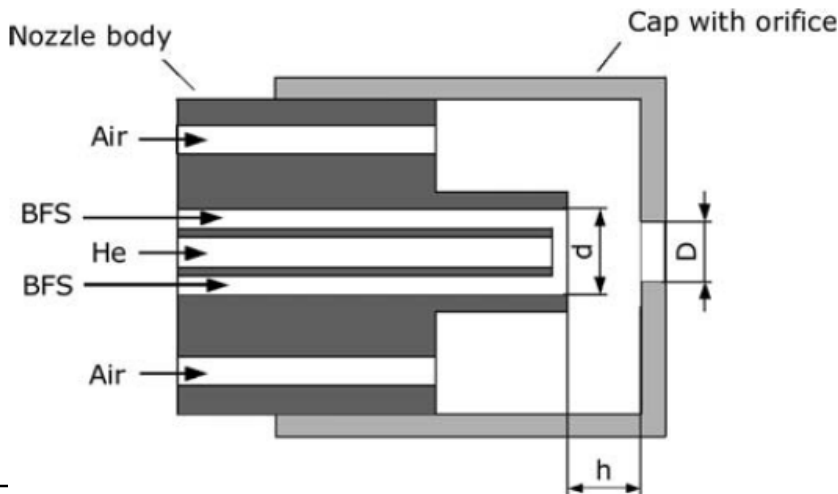
HELIUM-FILLED SOAP BUBBLES (HFSB)

Large-scale tomo-PIV

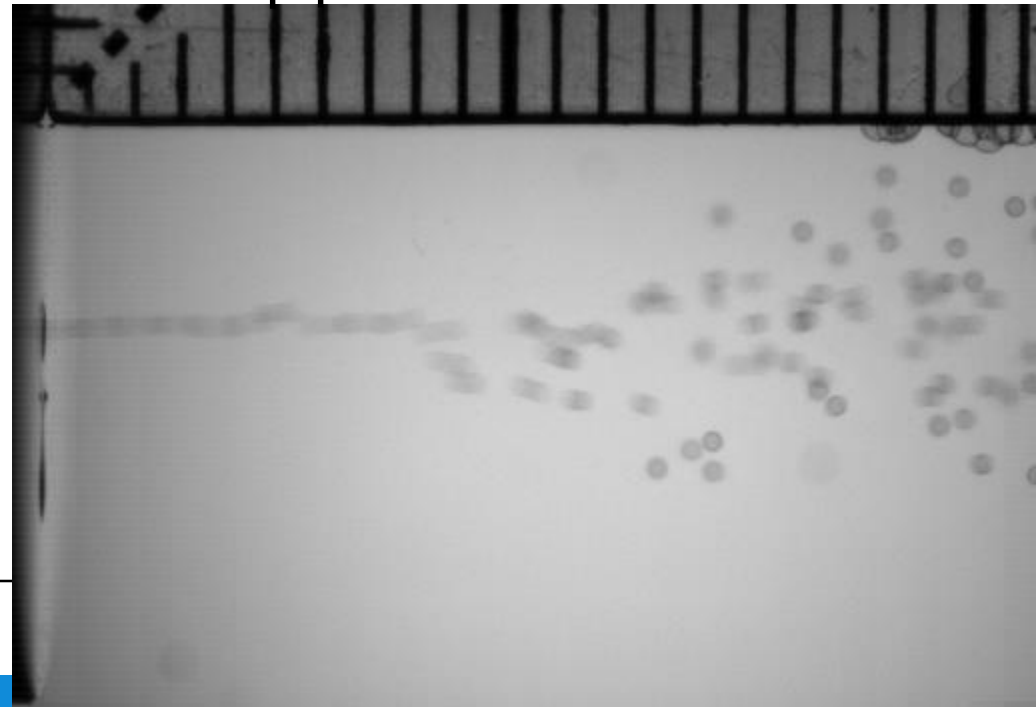
- Typical measurement volumes for PIV: $\sim 50 \text{ cm}^3$
- HFSB allowed measurements up to $>20,000 \text{ cm}^3$



Bubble generator

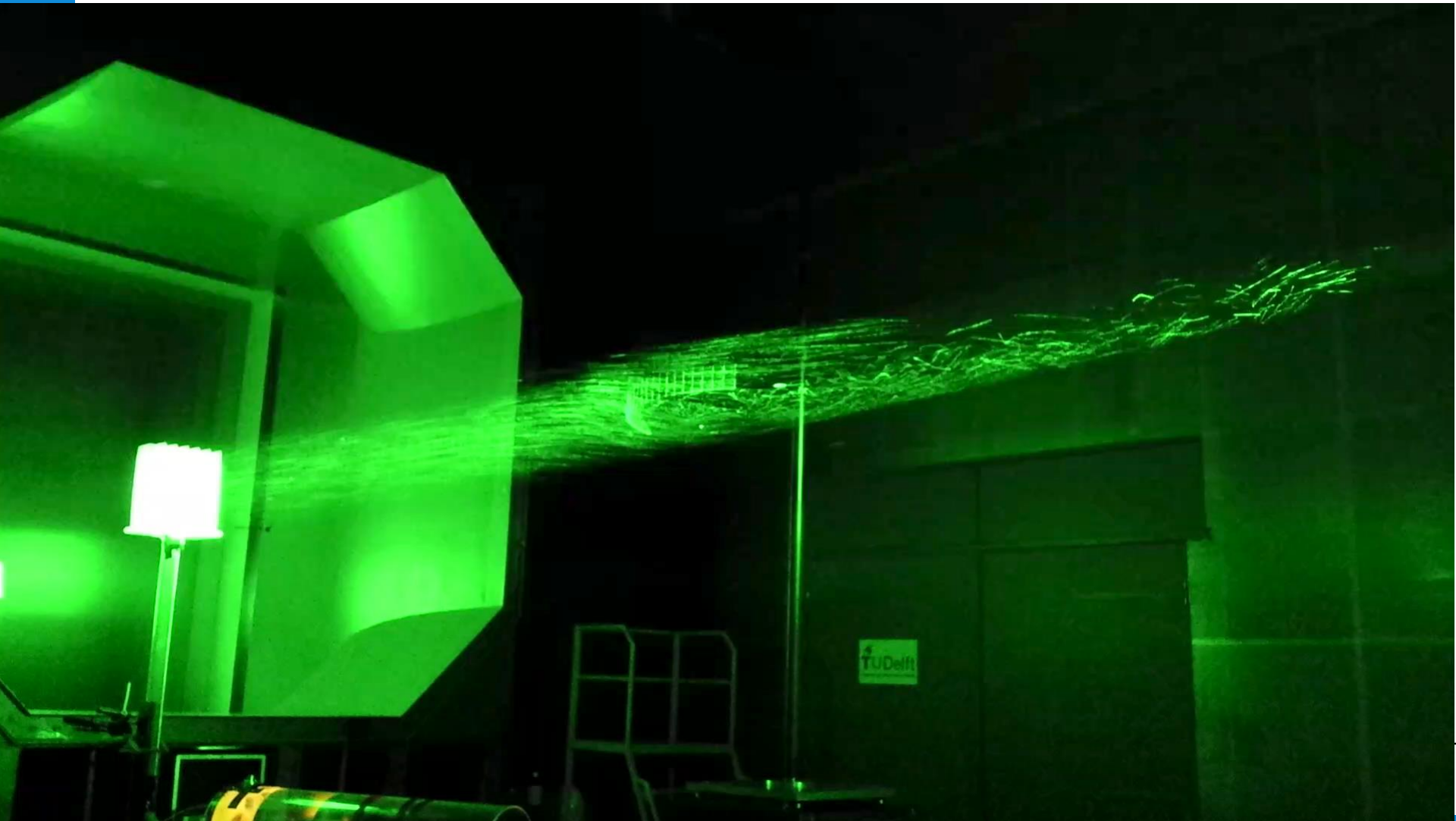


1 mm

A horizontal scale bar with a double-headed arrow, labeled '1 mm', is positioned above the PIV image to indicate the magnification level.

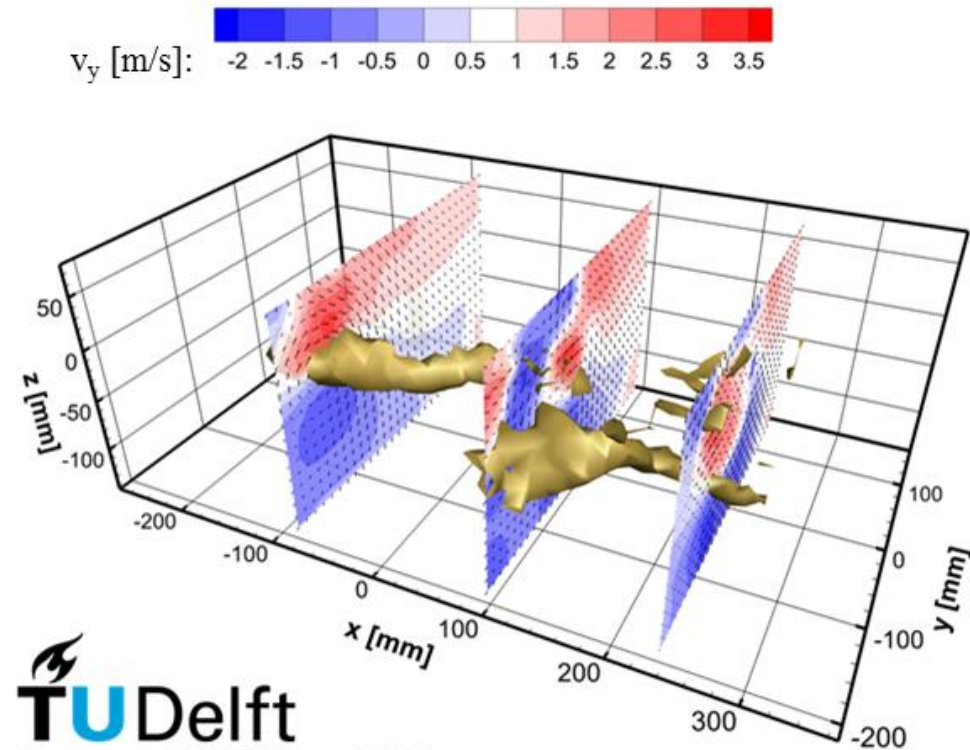
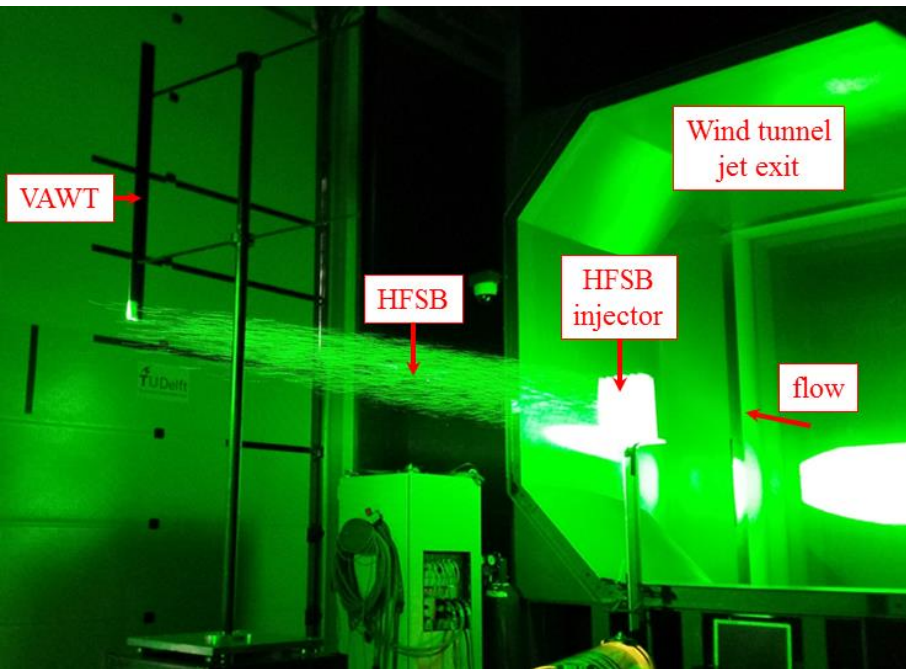
Large-scale tomo-PIV application

Vertical Axis Wind Turbine (VAWT)



Large-scale tomo-PIV on VAWT

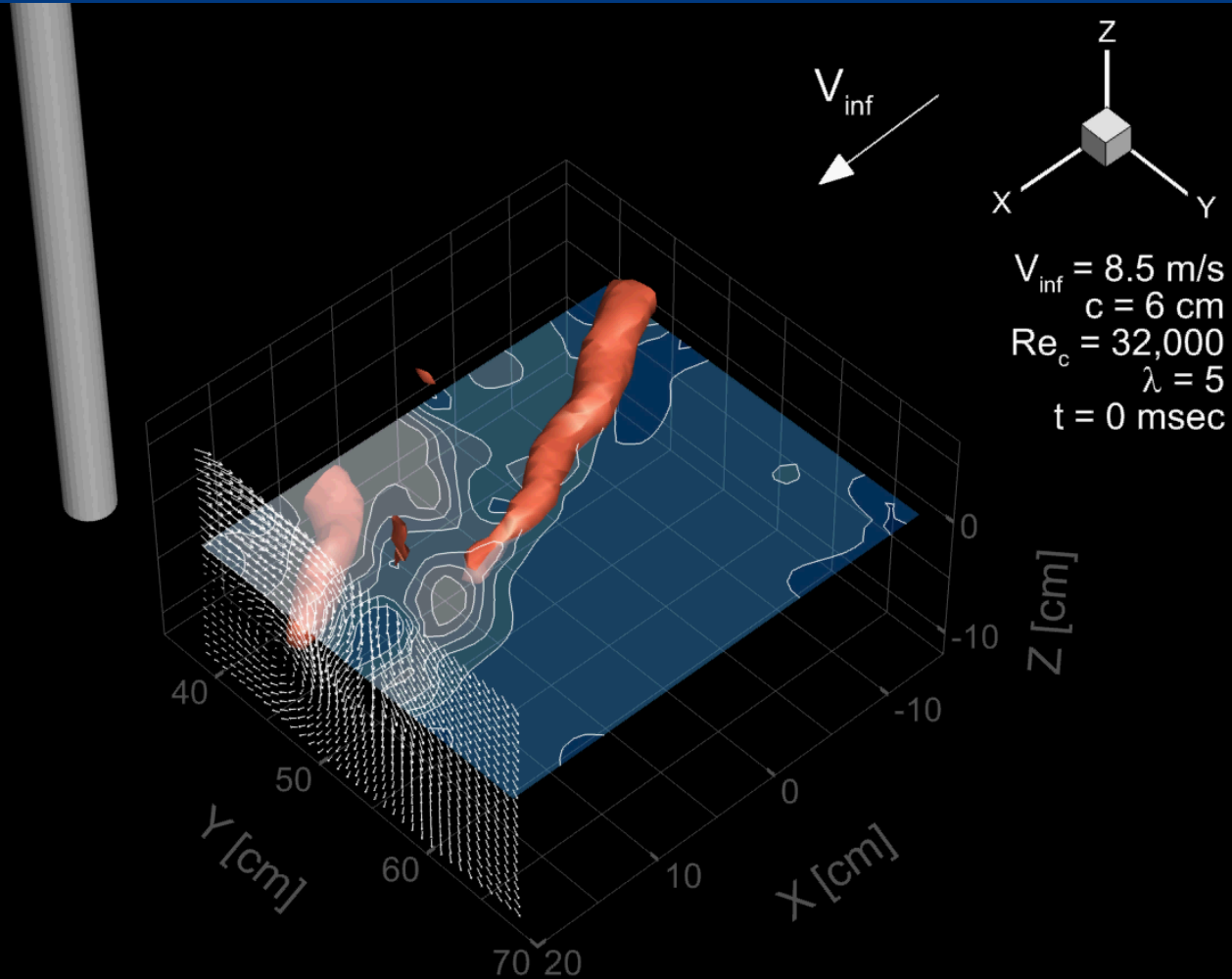
Quantitative results



TU Delft
Large scale TOMO PIV on a VAWT
Helium filled soap bubbles
 $V=5$ m/s, $TSR=5$
Isocontours of vorticity 200 rad/s

Large-scale tomo-PIV on VAWT

Quantitative results



Large-scale tomo-PIV for sport aerodynamics

➤ Current measurements are:

- **Static:** Athlete in static position in the wind tunnel test section
- **Blind:** Forces measured with balances – no link to the flow field



➤ Large-scale tomo-PIV allows:

- Quantitative flow visualization
- Tailored optimization of position, shape, garment
- On-site measurements

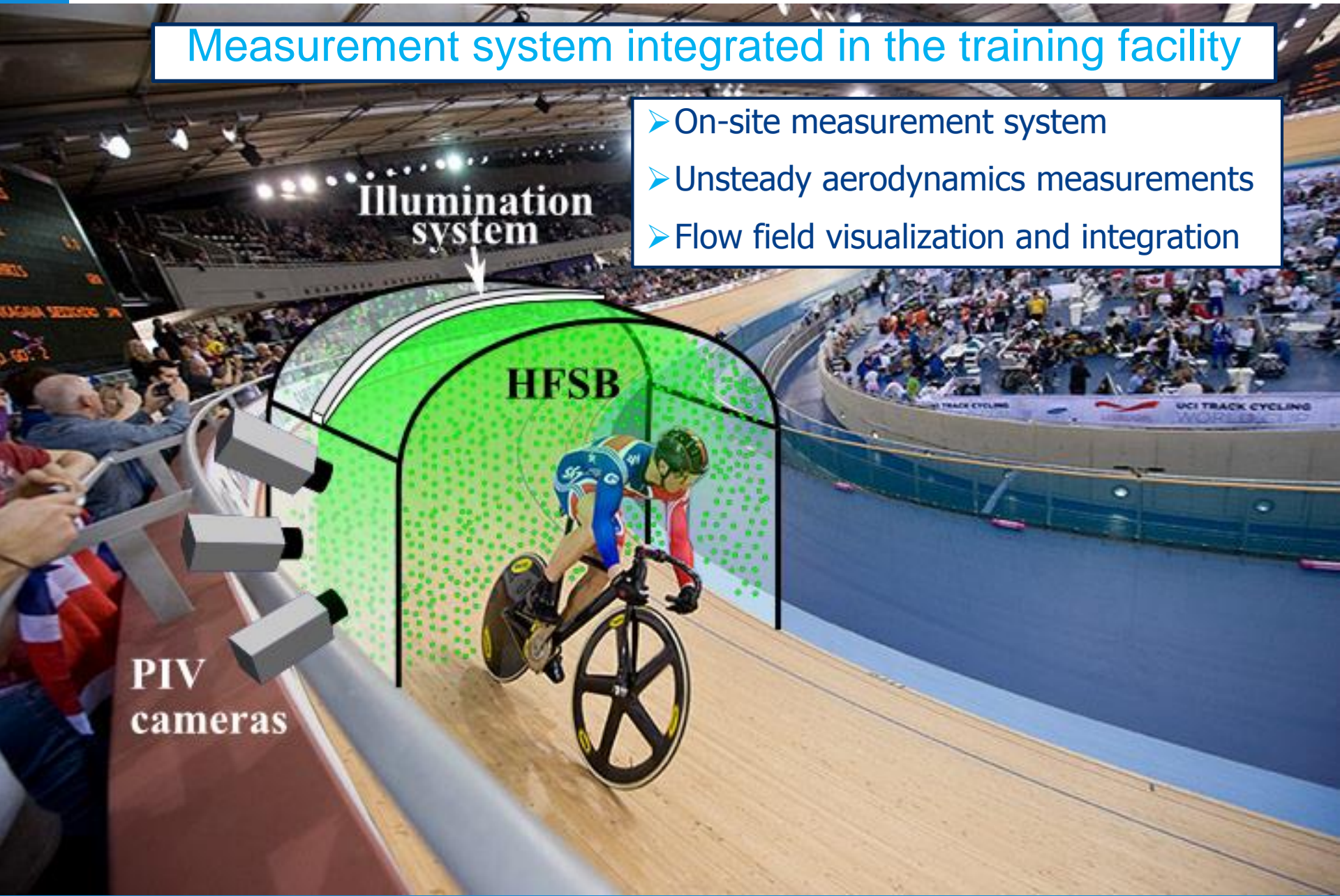
The “Ring of Fire” concept



The "Ring of Fire" concept

Measurement system integrated in the training facility

- On-site measurement system
- Unsteady aerodynamics measurements
- Flow field visualization and integration



Summary

- Particle image velocimetry allows non-intrusive velocity measurements
- Large-scale 3D measurement volumes via HFSB technology
- Aerodynamic forces from velocity fields
- Ring-of-fire: on-site 3D velocity and drag measurements
- 20-24 July: First experiment on scaled ring-of-fire at TU Delft

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