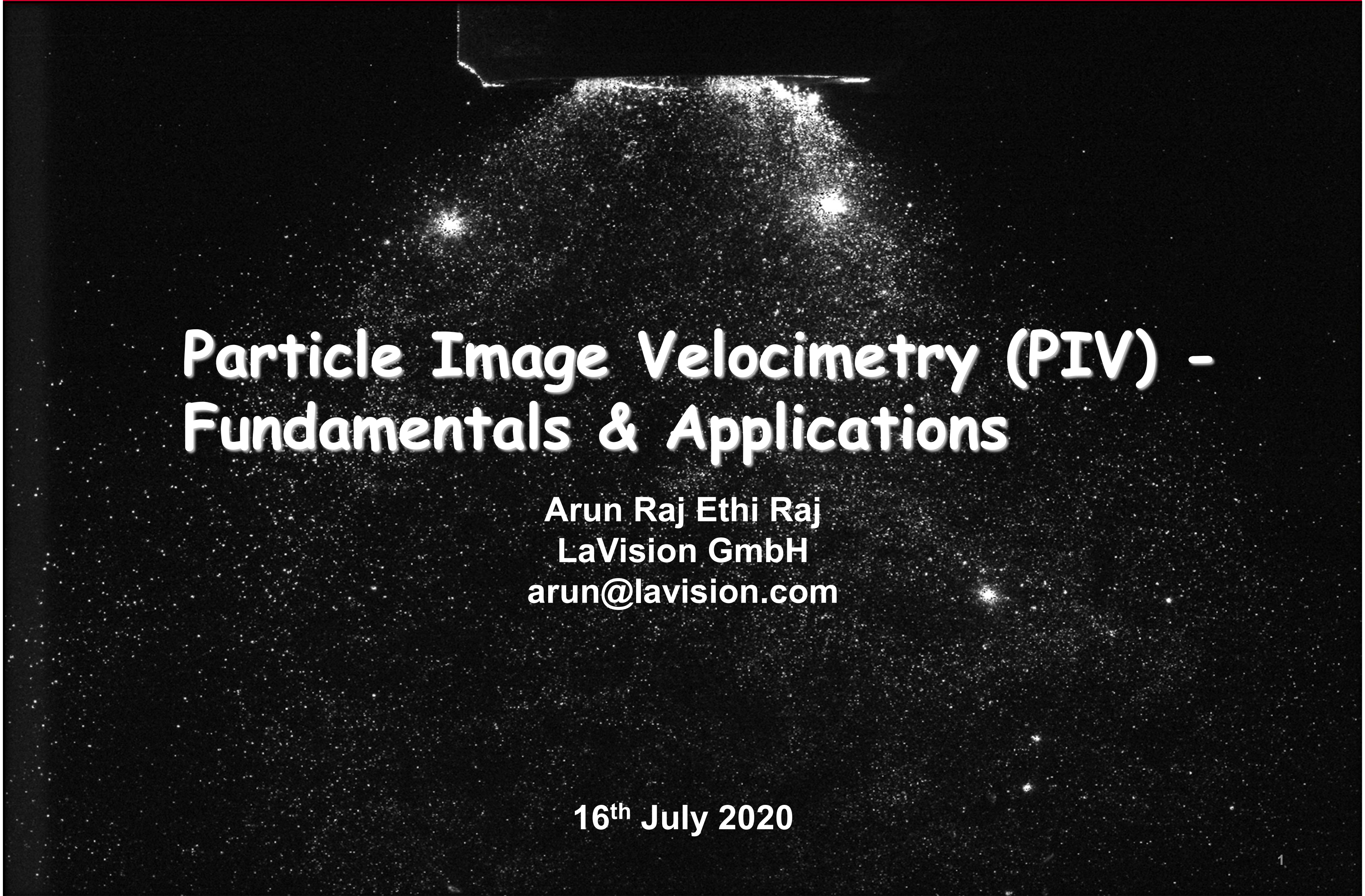


Particle Image Velocimetry (PIV) - Fundamentals & Applications

Arun Raj Ethi Raj
LaVision GmbH
arun@lavision.com

16th July 2020

LaVision – La(ser) Vision Technology

LaVision GmbH
founded in 1989
Goettingen (Germany)

LaVision Inc.
LaVision UK Ltd.
LaVision France
LaVision India

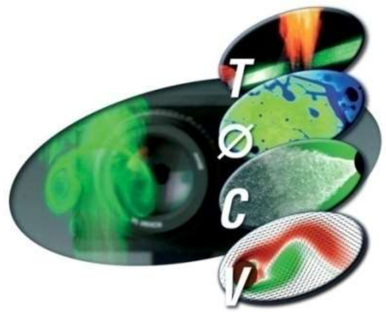
www.lavision.com

Laser Imaging: Techniques & Information

Flow, Spray & Combustion Visualization on Laser Light Sheets

	Velocity	Concentration total gas	species	Temperature	Size
PIV	✔				
LIF			✔	✔	
Rayleigh		✔		✔	
Raman		✔	✔	✔	
LII			✔		
Shadow					✔
IMI					✔

PIV: Particle Image Velocimetry
LIF: Laser Induced Fluorescence
LII: Laser Induced Incandescence
IMI: Interferometric Mie Imaging

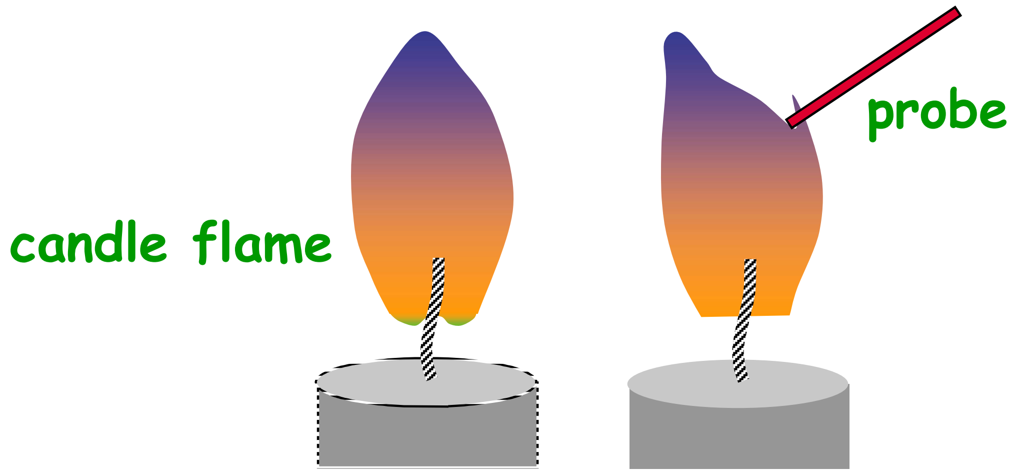


What is "Optical Flow Diagnostics"?

Optical flow diagnostics is the art of characterizing a flow in space and time by means of light scattering.

Why NON – Intrusive?

Usually, we need to bother about an intrusive probe if it is altering the flow, being measured/diagnosed

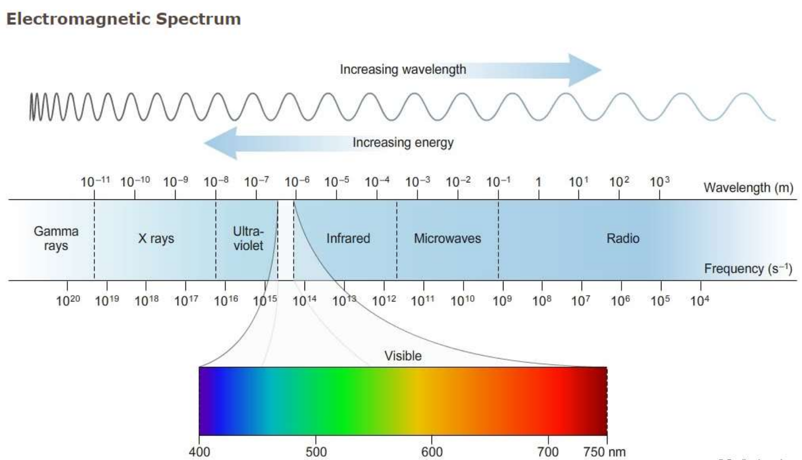


Why Optical ?

“Seeing is believing!!”

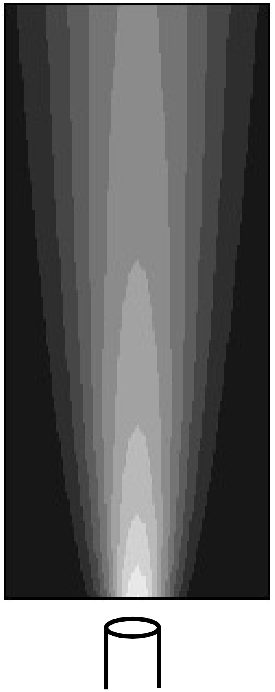
Optical => light => photons

Usually, 'optical diagnostics' includes some *UV, Visible, IR*, and even other regions of the electromagnetic spectrum.



Why laser imaging?

Conventional methods
(HWA, LDV)



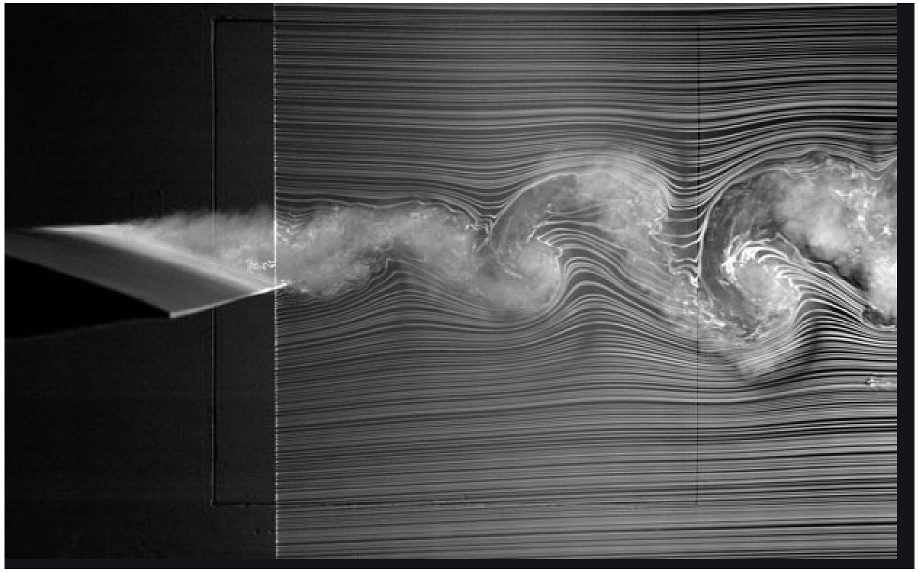
- single-point measurement
- traversing of flow domain
- time consuming
- only turbulence statistics

Laser Imaging technique: PIV

- whole-field method
- non-intrusive (apart from tracer)
- instantaneous flow field

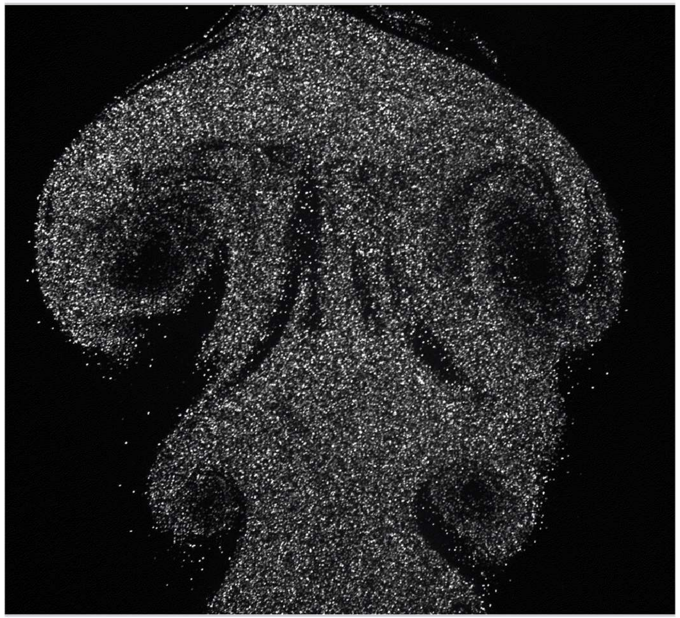
Visualization Vs Measurement

QUALITATIVE DATA



TRACER PARTICLES ARE FOLLOWING STREAMLINES OF THE FLOW

QUANTITATIVE DATA



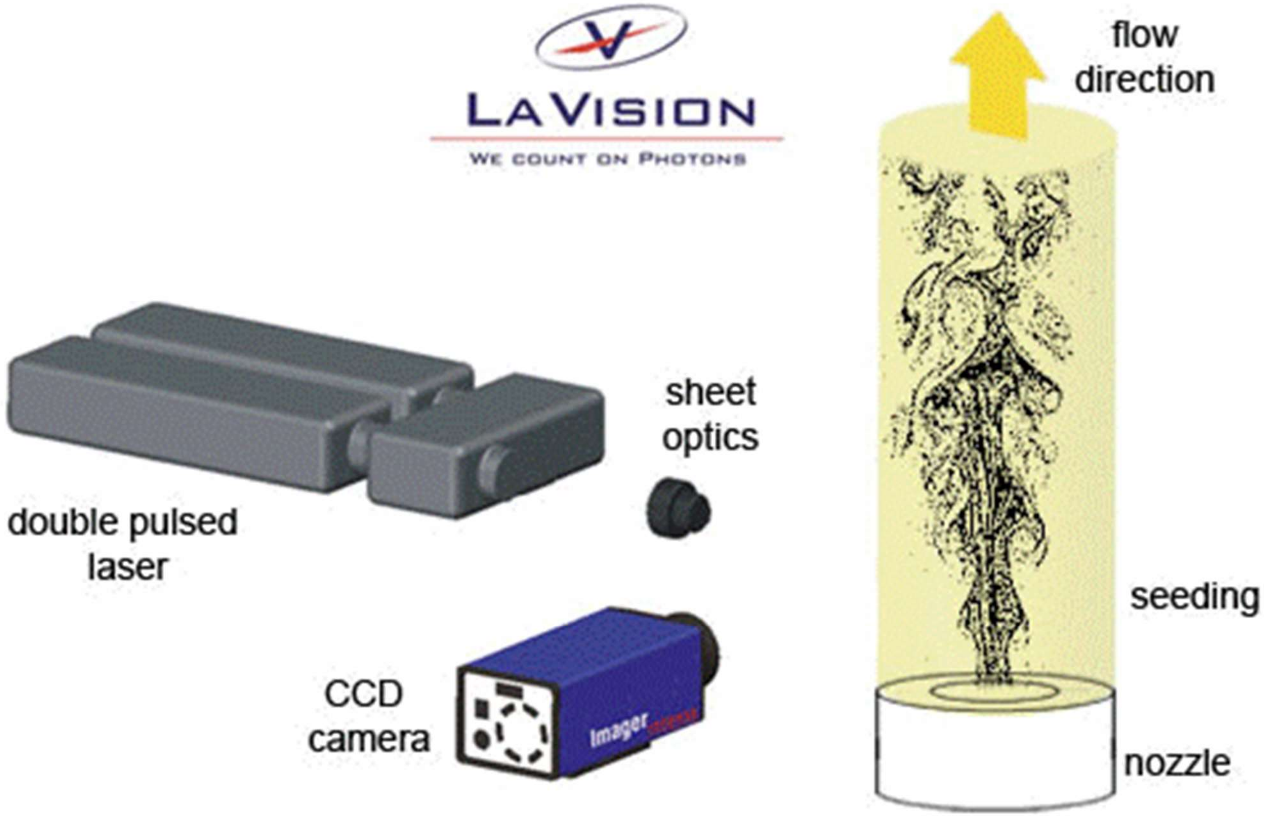
TRACER PARTICLES ARE DISTRIBUTED HOMOGENEOUSLY

Planar Imaging

Major components used in Planar imaging:

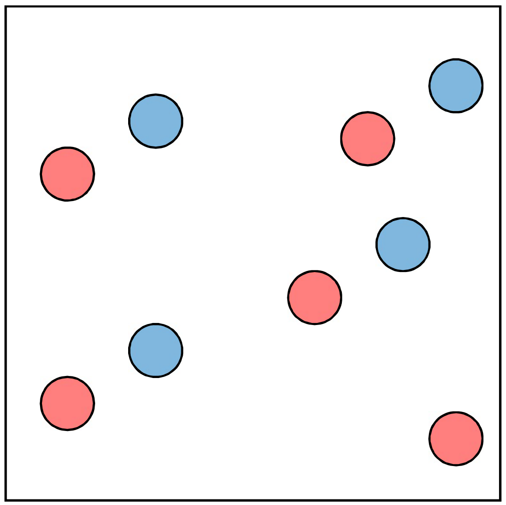
- **Illumination source (Laser beam)**
- **Light sheet optics**
- **Flow seeding**
- **Camera**
- **Timing Circuit (Synchronizer)**

PIV - Principle

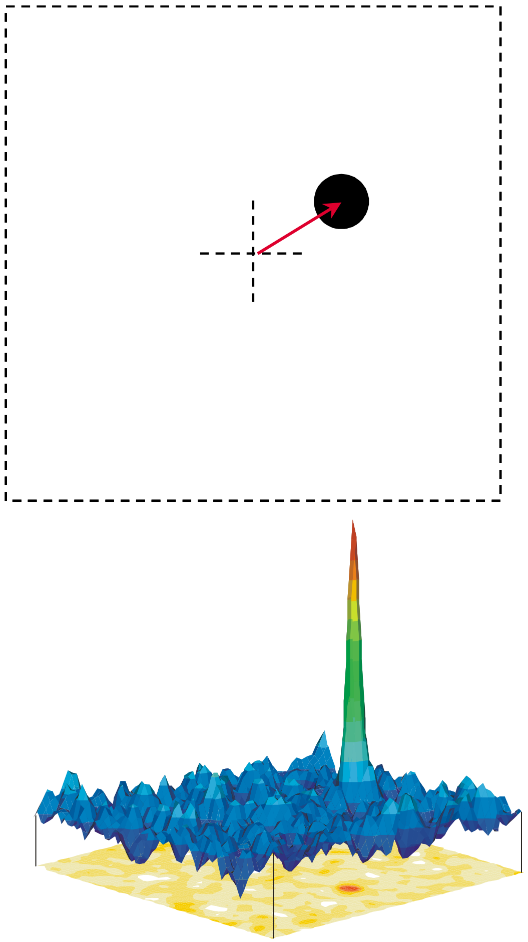


How the cross correlation works

Particle image



Correlation plane

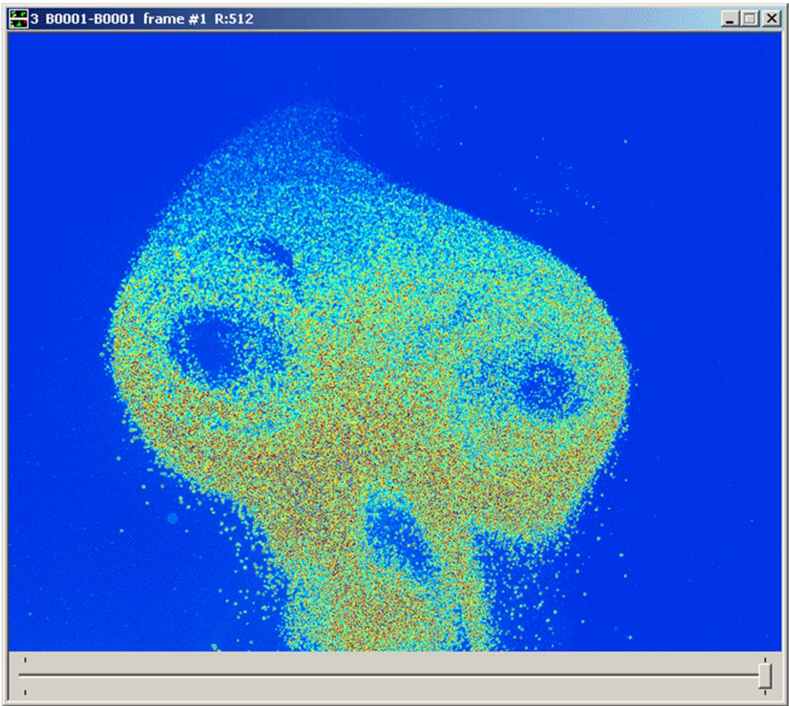


PIV Design Rules

- Image density $N_I > 10$
- In-plane motion $|\Delta x| < ¼ D_I$
- Out-of-plane motion $|\Delta z| < ¼ \Delta z_0$
- Particle image diameter $d_\tau / d_r = 2\text{-}4$

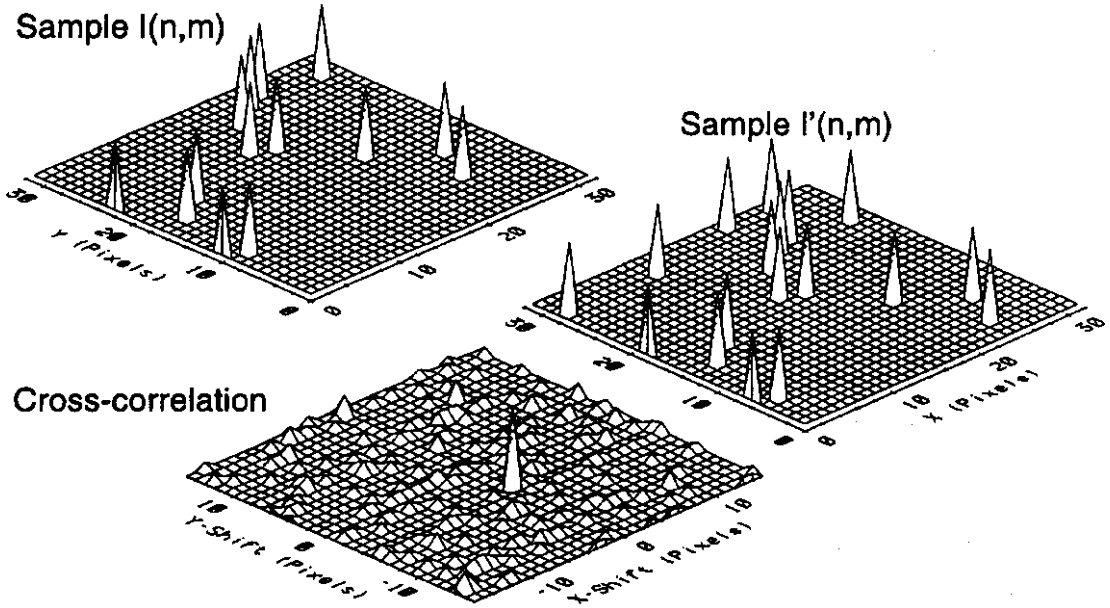
N_I = particle per int. window
D_I = int. window size
Δz_0 = light sheet thickness
d_t = particle image diameter
d_r = pixel size of CCD sensor

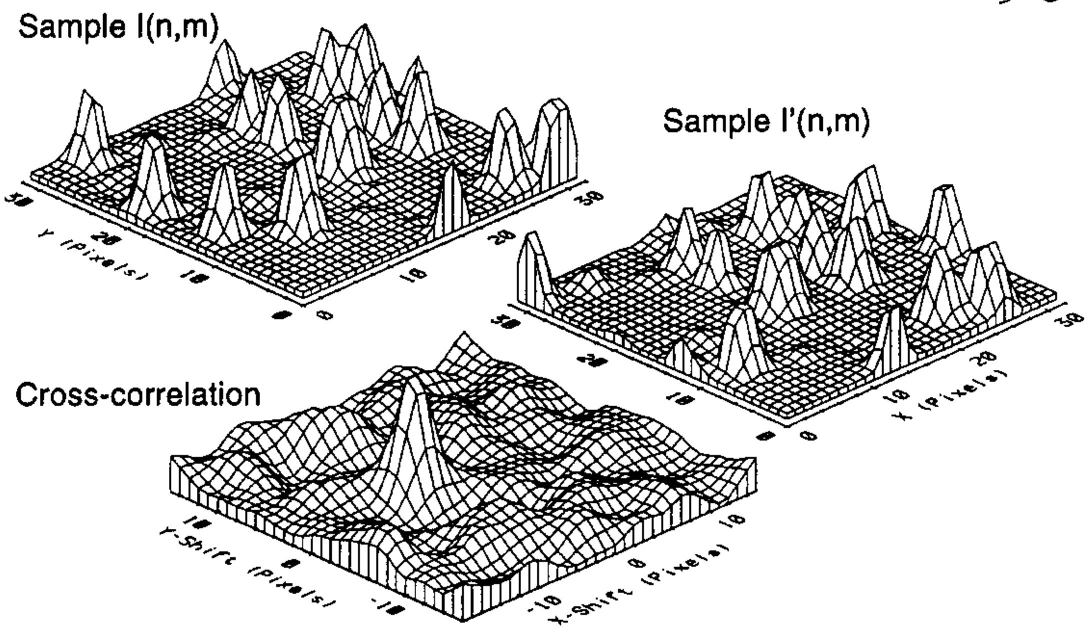
Adrian R; Westerweel J (2010) “Particle Image Velocimetry”



Examples of digital correlation

correlation peak is convolution of particle image and particle separation





Particle image diameter <1pixel can cause a bias during vector calculation

Remedy: • particle sizes at least 2 pixels (e.g. with slight defocussing

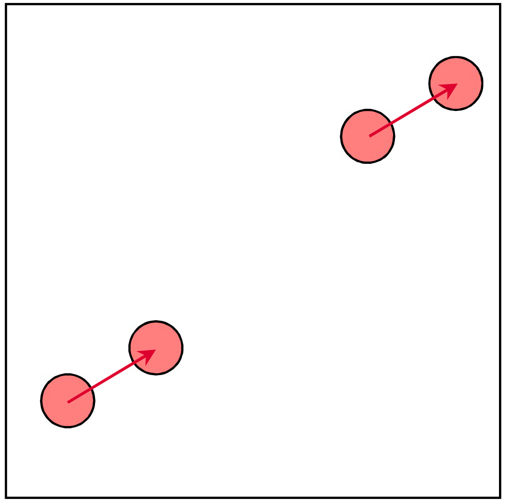
Particle Tracking Velocimetry (PTV)

Principle:

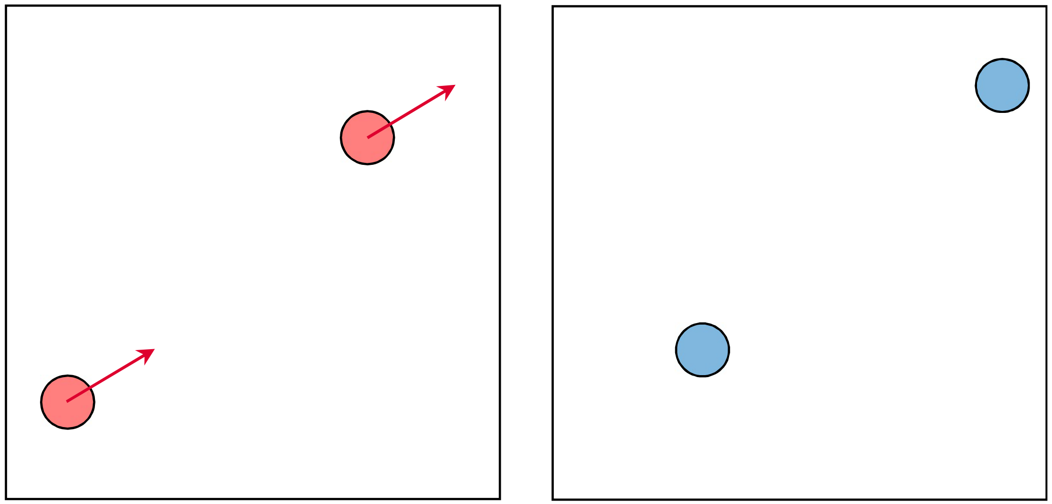
- particle detection and determination of its position
- tracking of single particles by particle matching

Remarks:

- limited to low seeding density (<0.002 ppp)
- 2D PTV suffers from low statistics, higher validation requires an extension to stereo / 3D / higher temporal sampling

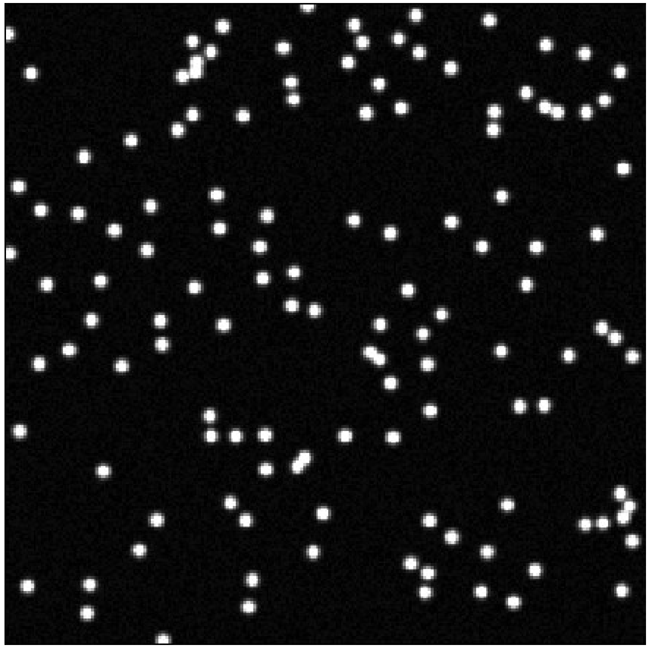


single frame

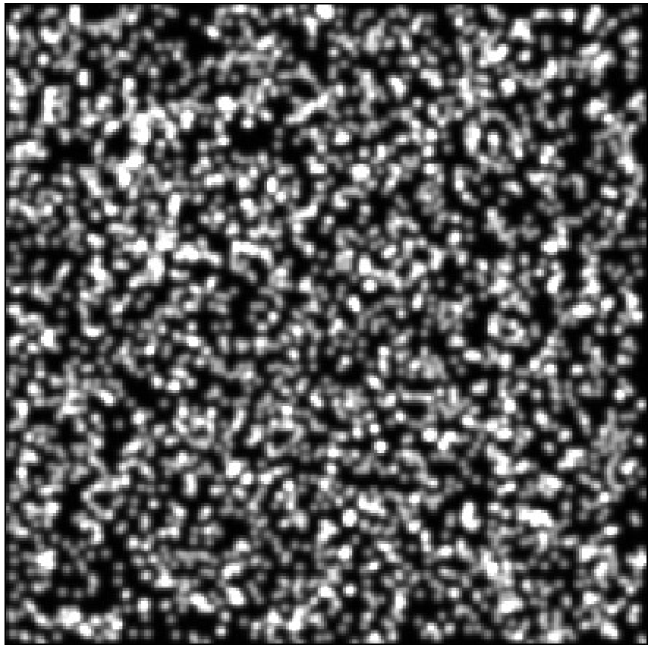


double frame

Particle density - PIV vs. PTV



DNS, ROI 256x256px, 0.002ppp



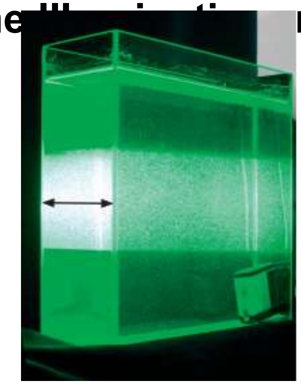
DNS, ROI 256x256px, 0.05ppp

DNS = direct numerical simulation
ROI = region of interest
ppp = particle per pixel

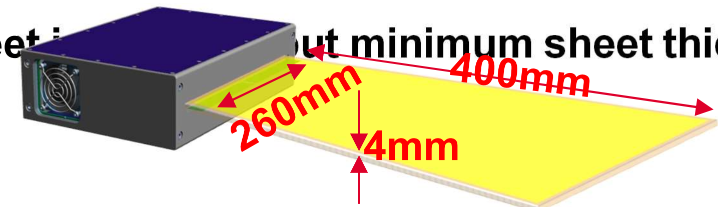
Illumination Source

- **LASER (Light Amplification by Stimulated Emission of Radiation)**

  - **Continuous Laser (low velocity appln)**
  - **Pulsed Laser**
    - **Single Cavity (low velocity appln)**
    - **Double Cavity (low to Supersonic flow appln)**
  - **Laser sheet used for Planar Imaging**
  - **Laser Volume Illumination used for Tomographic Imaging**

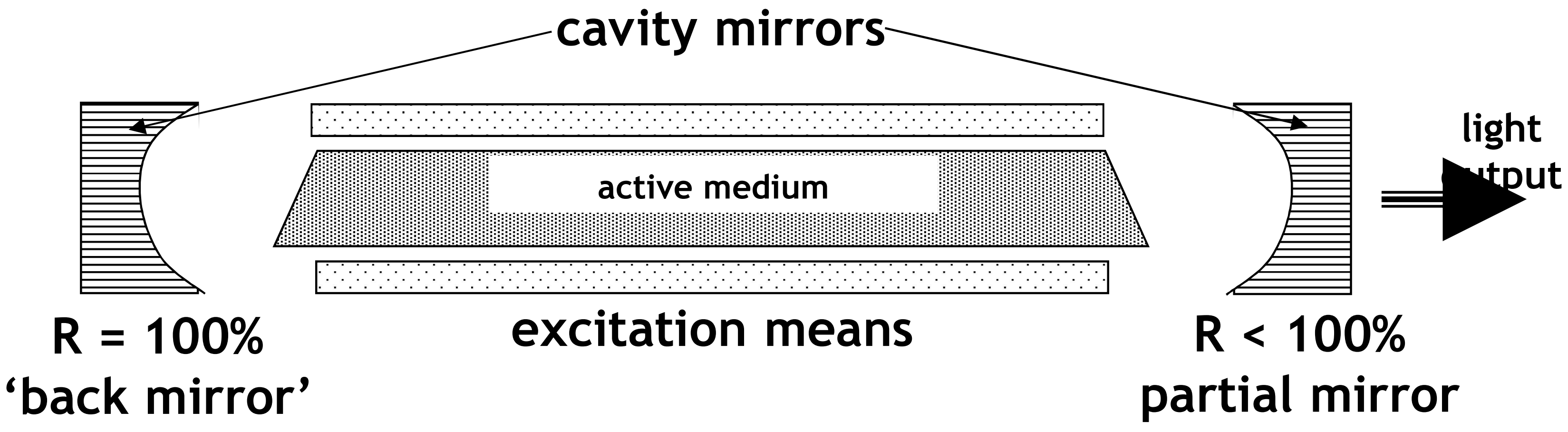


- **LED Light (low velocity appln)**
  - **Best suited for low velocity Tomographic application**
  - **Sheet i ... ut minimum sheet thickness is abo**



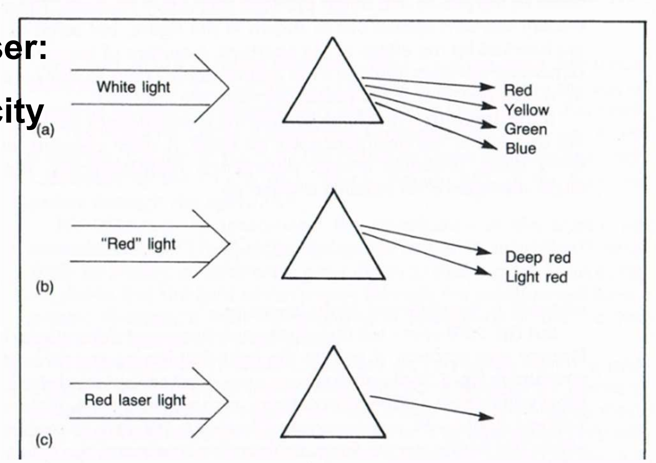
LED-Flashlight 300

Components of a laser

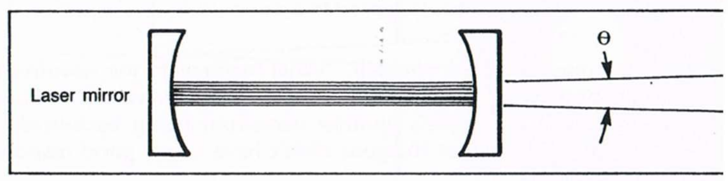


Characteristics of Laser:

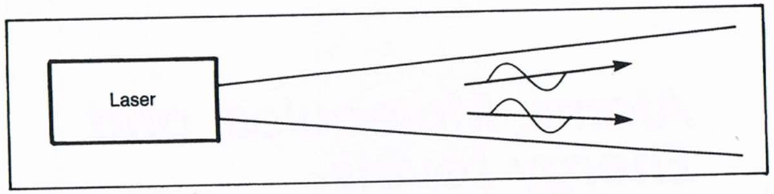
1. Monochromaticity



2. Directionality



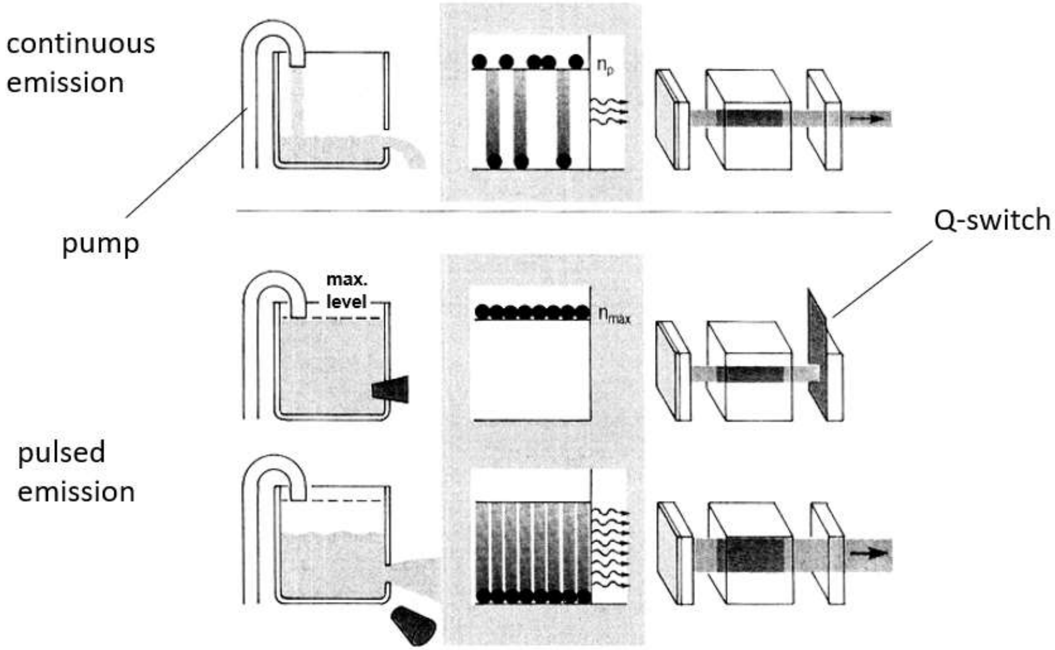
3. Coherence (same wavelength, same direction and the same phase)



Essential components:

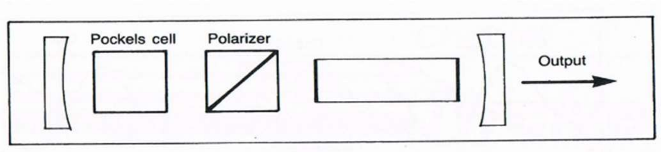
- active medium emitting and amplifying light
- selective pump mechanism creating population inversion
- optical cavity or resonator (usually via mirrors)

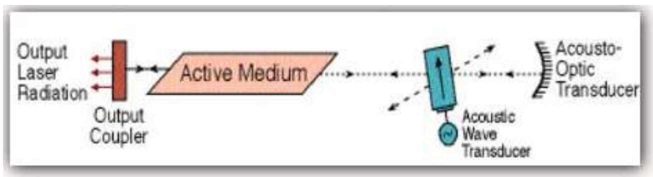
Pulsed Laser

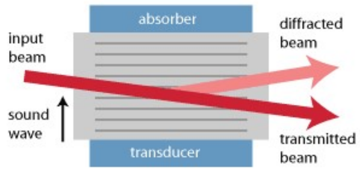


QSWITCH types

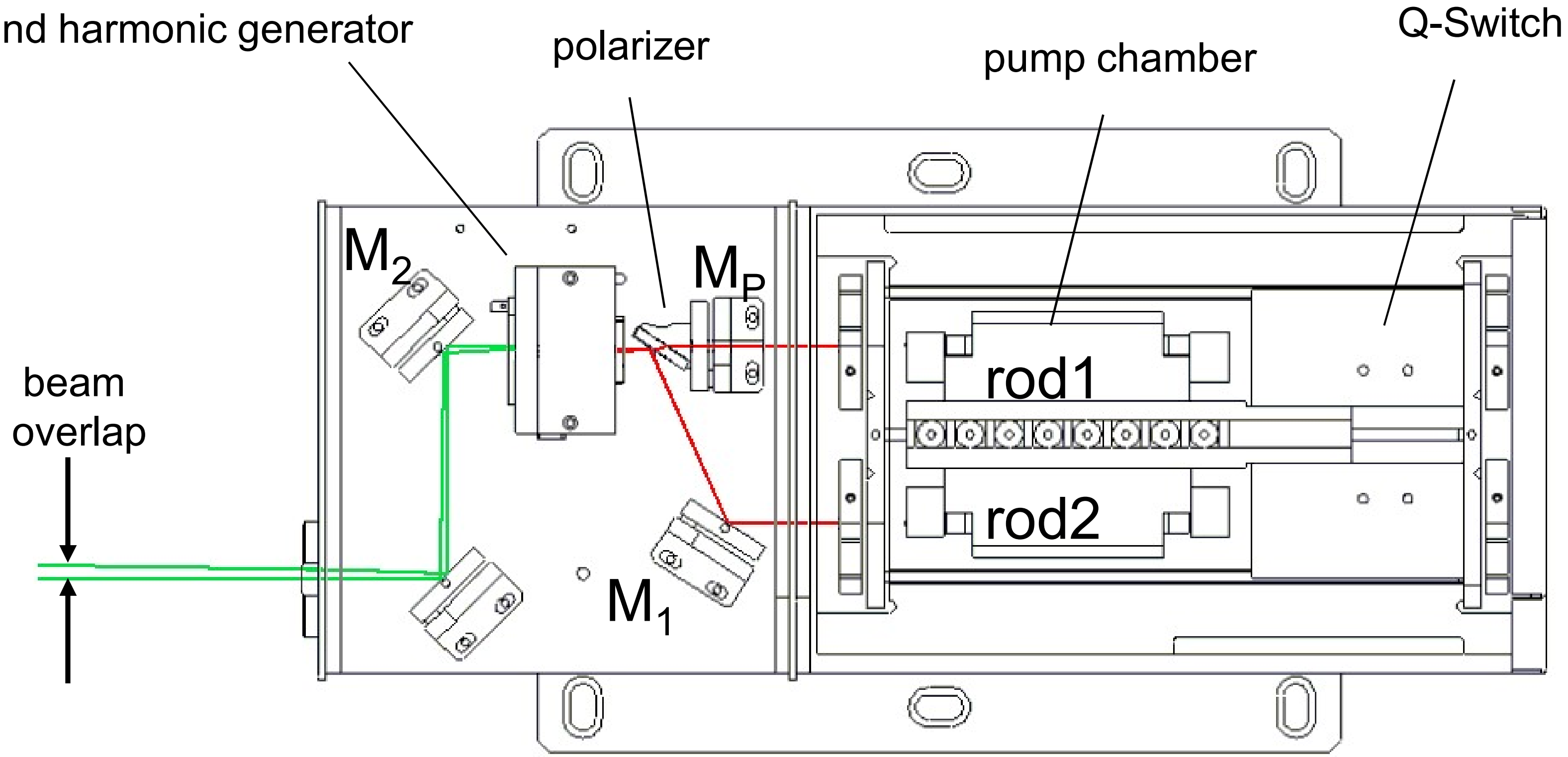
- Electro Opto Modulator (EOM)
- Acousto Opto Modulator (AOM)







Double pulse Nd:YAG Laser



A *second harmonic* ("2*w*") *generator* is a non-linear crystal used for doubling the frequency (or halving the wavelength)

- Typically needed for Nd:YAG lasers which operate at a fundamental frequency of 1064 nm (IR) to obtain visible green light at 532 nm

Third harmonic ("3*w*") and fourth harmonic ("4*w*") also available

- 3*w* (355 nm)
- 4*w* (266 nm)

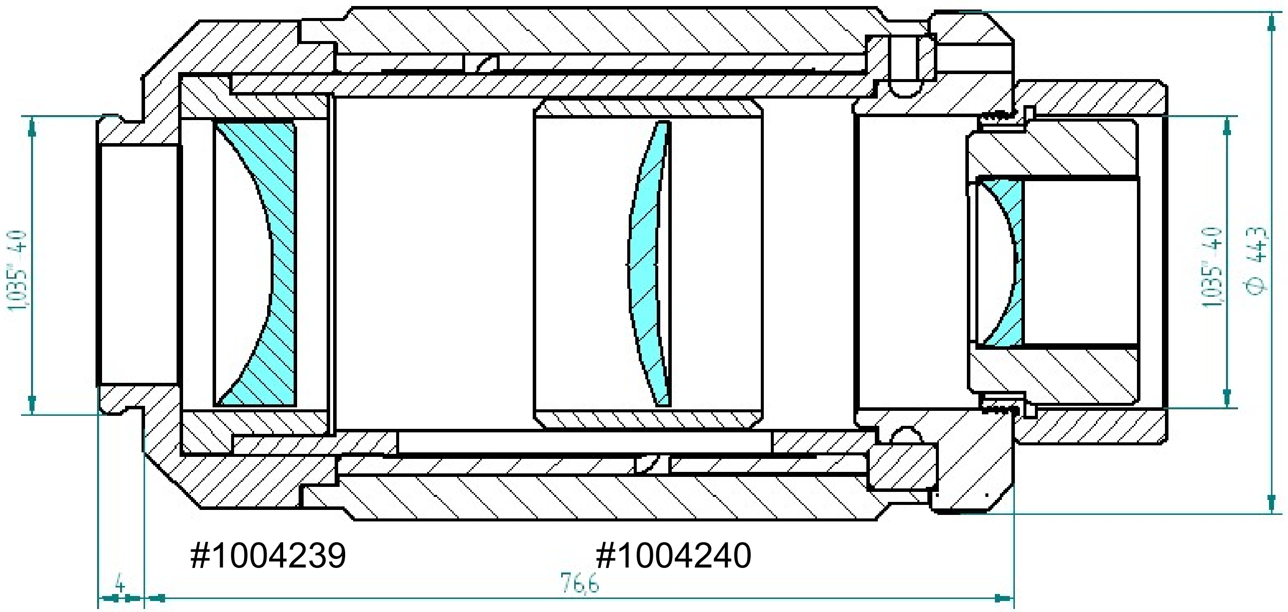
Light sheet optics

cylindrical
lens can be exchanged:

#1002019 f = -20 mm
#1002018 f = -10 mm
#1001066 f = -6 mm
#1001059 f = -3 mm

separation is adjustable

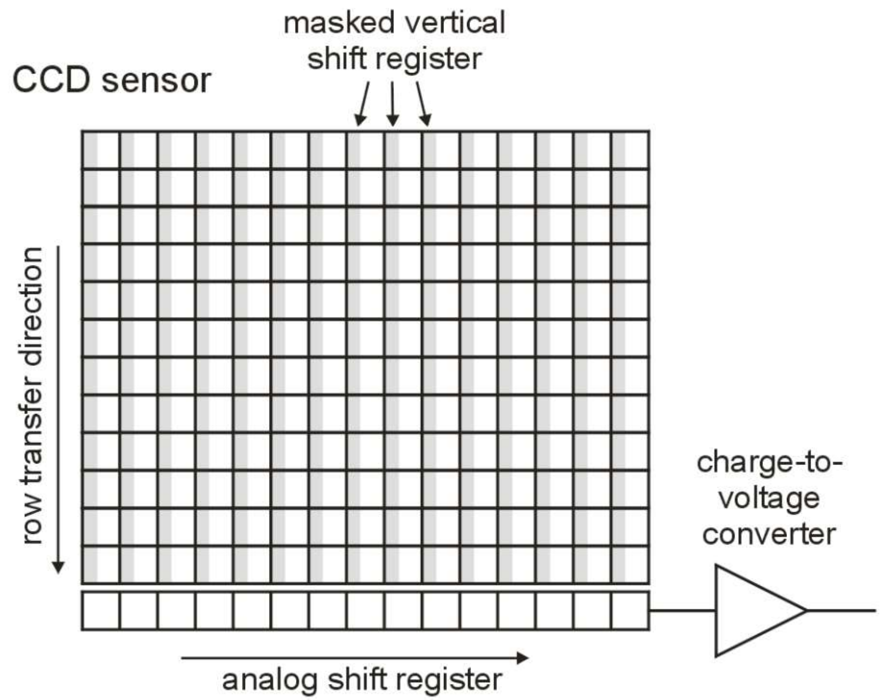
laser

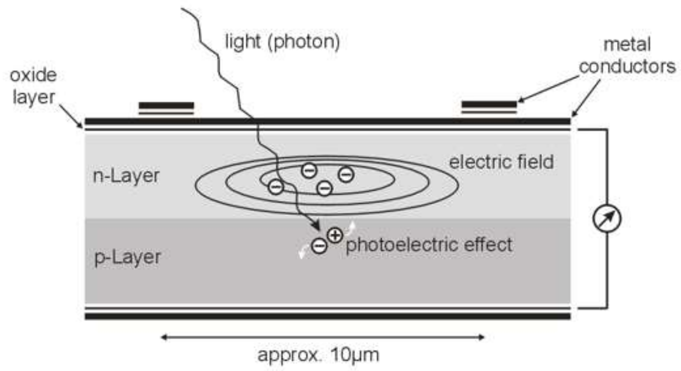


#1004239

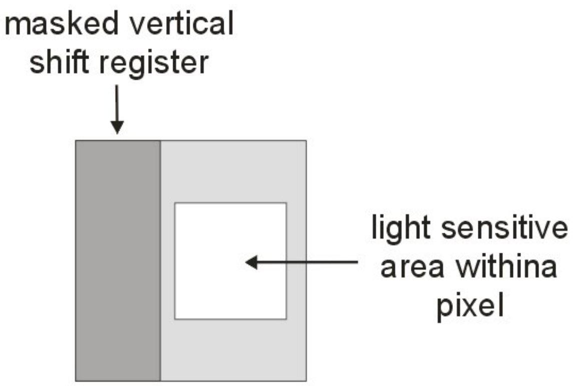
#1004240

CCD sensor: Full frame Interline transfer





Simplified pixel layout

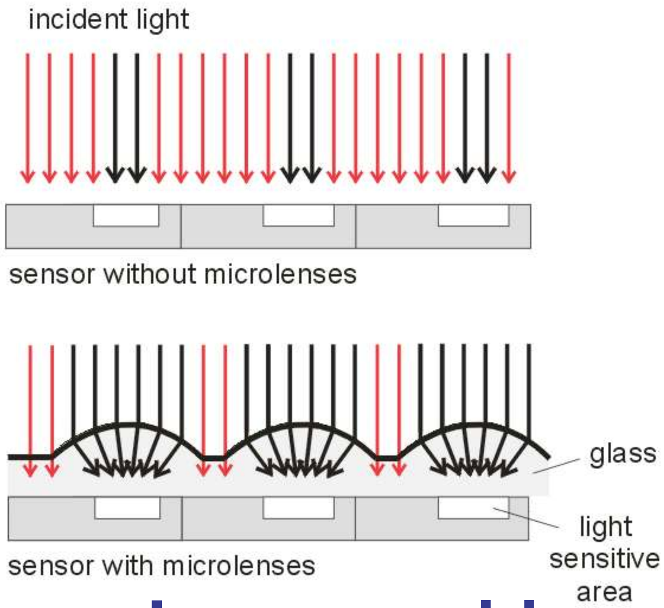


Advantages:

+ Fast frame transfer <1µs
+ Electronic Shutter
+ More sensitive in green

Drawbacks:

- Reduced fill factor

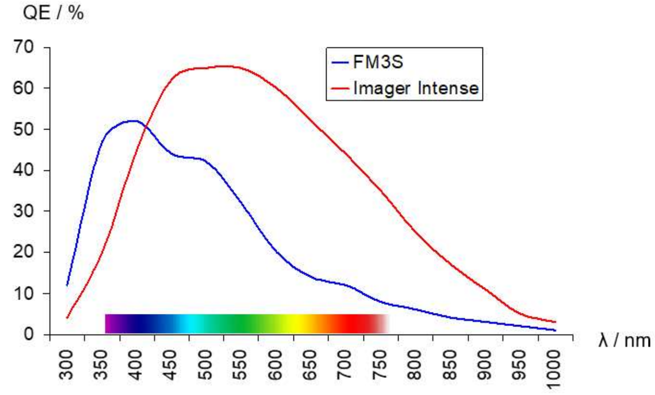


Lens on chip

CCD parameters

Quantum Efficiency:

QE = sensitivity S on a percentage scale



$$S = \frac{\text{no of collected photoelectrons}}{\text{no of incident photons per pixel}}$$

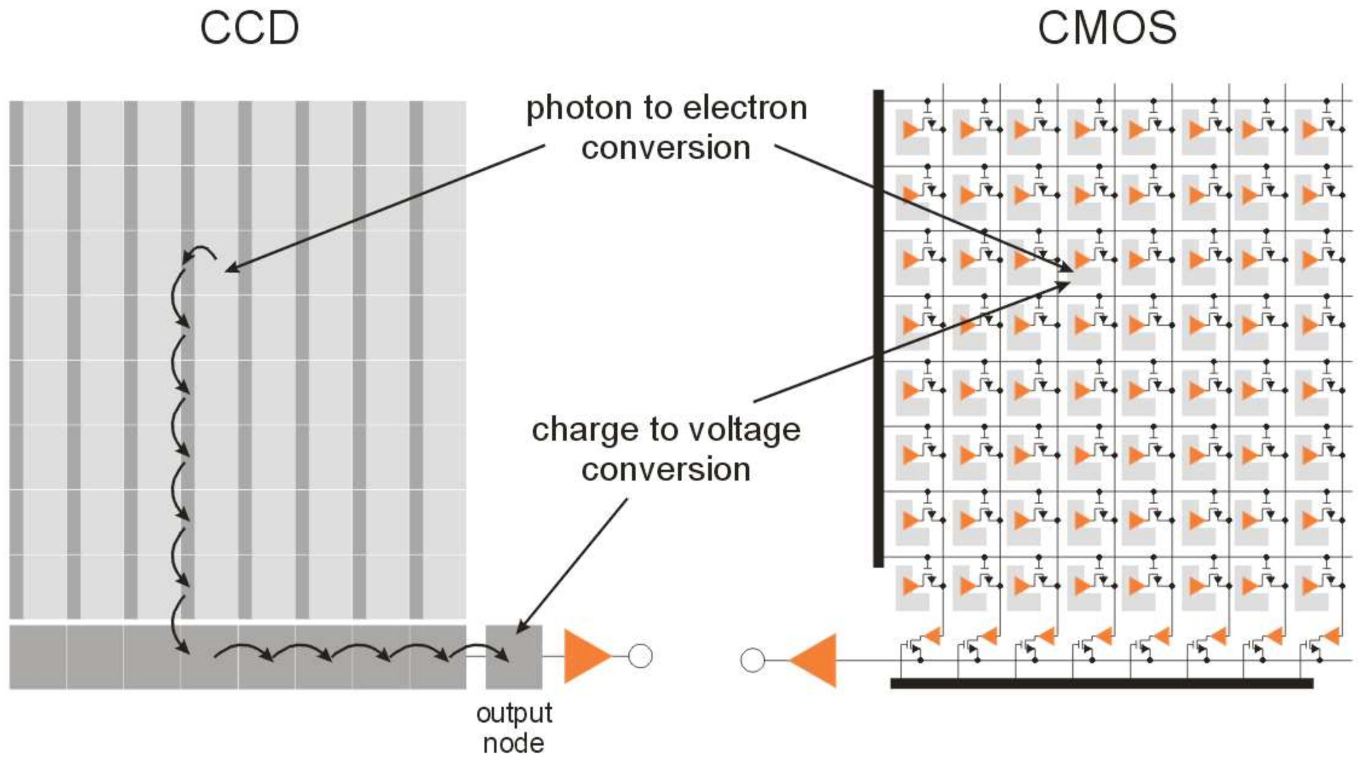
Spatial Resolution:

Higher Pixel resolution = Higher Spatial Resolution

Dynamic Range:

CCD vs CMOS

CCD: moves charge from pixel to pixel and convert it to voltage at output node
CMOS: converts charge to voltage inside one pixel



- CMOS cameras are much faster (parallel readout)
- CMOS cameras are less sensitive at 550nm (approx. factor 2)
- CMOS cameras show higher dark noise (factor 5-10)
- CMOS cameras don‘t show blooming effects
- CMOS sensors show inhomogeneous sensitivity (1.5% vs <0.5% for CCDs)

Seeding the flow

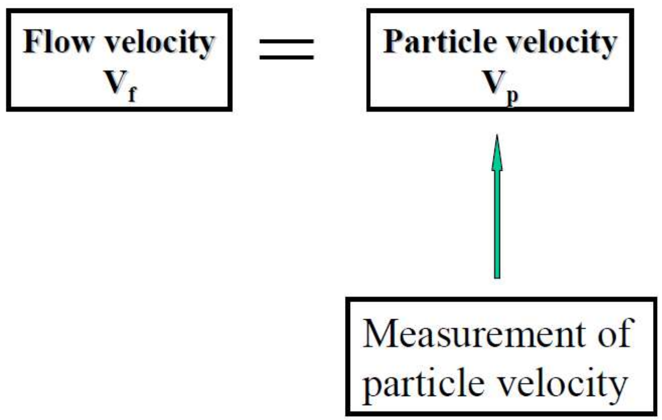
flow under investigation is usually transparent and clean
⇒ some additional particles must be added to gather stray-light

Problems:

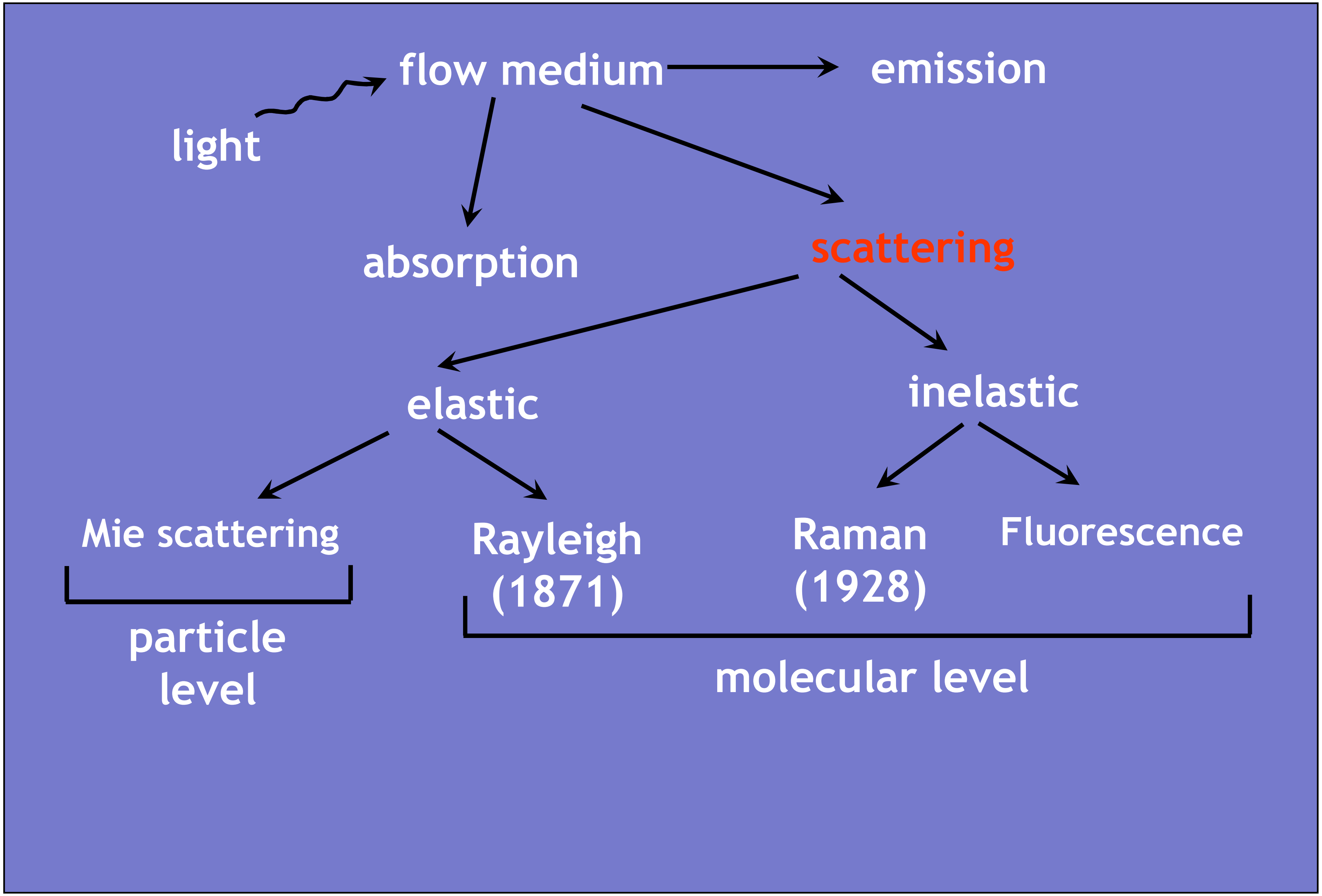
- provide sufficient seeding in the field of view
- slip of the particles (different density)
- contamination of the test rig
- particle size is important parameter

Inherent Assumptions

- tracer particles follow the fluid motion
- small to follow fluid motion
- should not alter fluid or flow properties (e.g. in two phase flows)
- density matched
- large enough to be visible

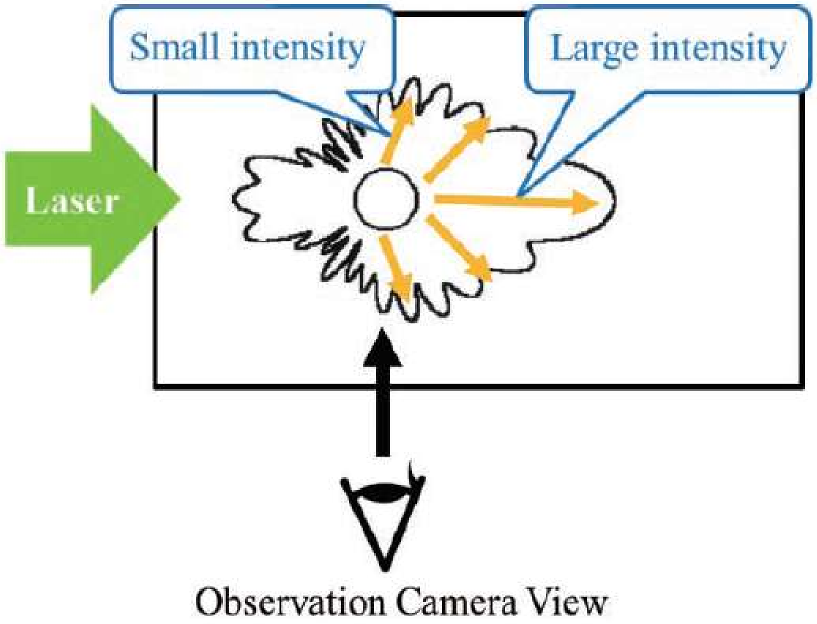


Light Interaction with flow medium



Mie scattering

- For Spherical particles with diameters larger than the wavelength of the incident light, MIE scattering theory can be applied (Rayleigh Scattering theory, d < wavelength)
- PIV is using MIE scattering
- highest intensity in forward direction
- 90° scattering with lower intensity



qualitative Mie scattering intensity distribution for one particle

Particles

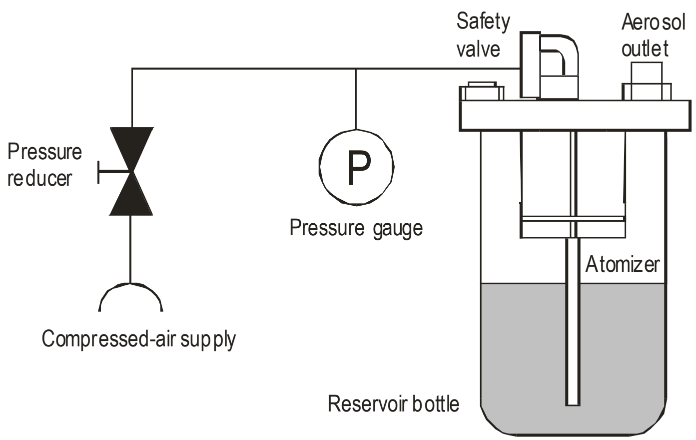
Type	Material	Mean diameter [μm]	Flow
Liquid	DEHS	0.5-1.5	air
	Vegetable oil	0.5-1.5	air
Solid	Glass spheres	10	water
	Polystyrene	10-100	water
	Metal oxide	2-7	flame
Gaseous	Oxygen bubbles	50-1000	water

The specific weight of particles has to be selected properly according to observed flow medium.

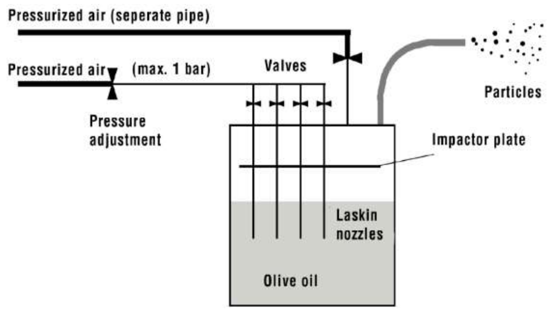
Seeding Generator for air appln

Aerosol generator

- generates poly-disperse aerosols
- for usage with DEHS, vegetable oil, etc



Laksin Nozzle



PIV Part 40 (DLR)

Fog Generator

Vaporizing fog generator

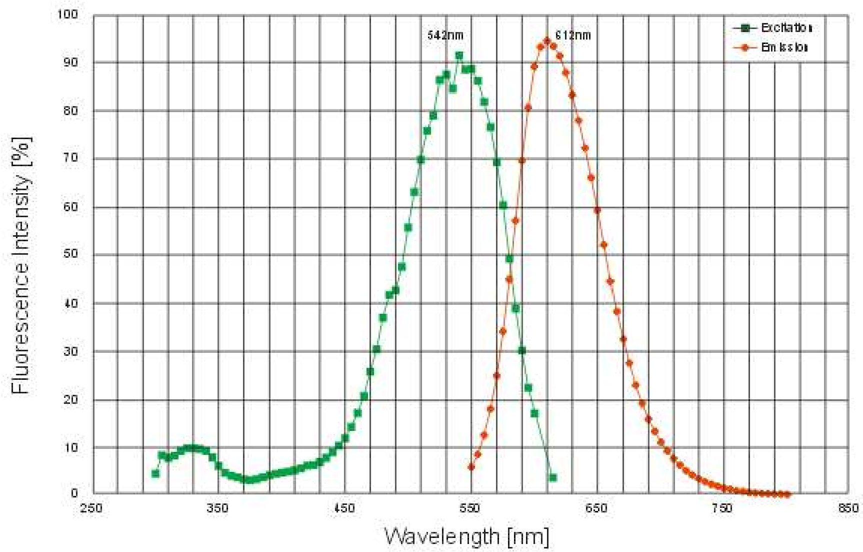
- very small particles
- high seeding density
- seeding density is difficul to control

Particles for seeding liquid flow

Polyamide Particles : almost perfectly spherical particle shape

- Offered particle size 20, 60, 100 microns
- Particle density close to water density
- Bigger particle size and density close to water leads to a strong scatter of the laser light

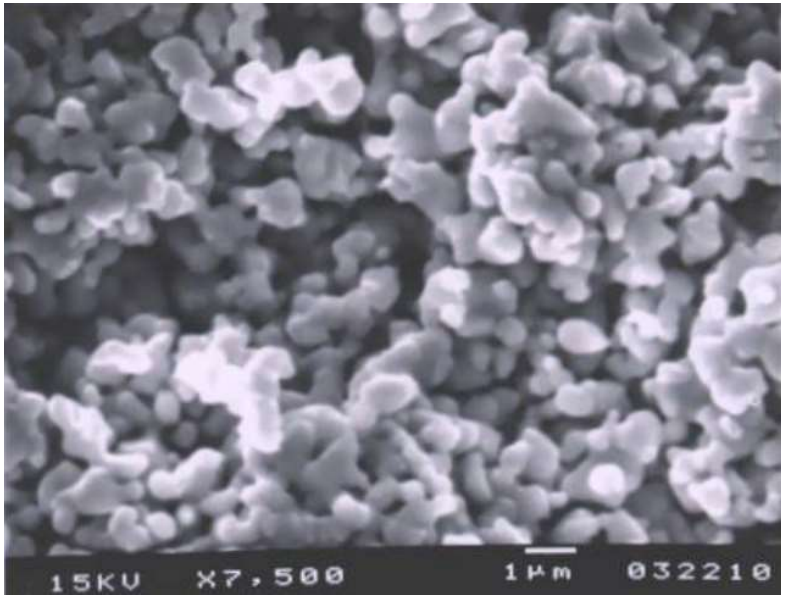
Fluorescent particles



0.3 µm, Rhodamine 6G, Polystyrene, suspension, 15 ml
0.5 µm, Rhodamine 6G, Polystyrene, suspension, 15 ml
0.9 µm, Rhodamine 6G, Polystyrene, suspension, 15 ml
2,0 µm, Rhodamine 6G, Polystyrene, suspension, 10 ml
2.0 µm, Rhodamine B, Polystyrene, suspension, 10 ml
10 µm Rhodamine B, Melamine, suspension, 10 ml
20 - 50 µm, Rhodamine B, PMMA, powder, 1 g
20 - 50 µm, Rhodamine B, PMMA, powder, 25 g
20 - 50 µm, Rhodamine B, PMMA, powder, 50 g
20 - 50 µm, Rhodamine B, PMMA, powder, 100 g
1 - 20 µm, Rhodamine B, Polystyrene, powder,1 g
1 - 20 µm, Rhodamine B, PMMA, powder, 1 g

Particles for seeding combustion flow

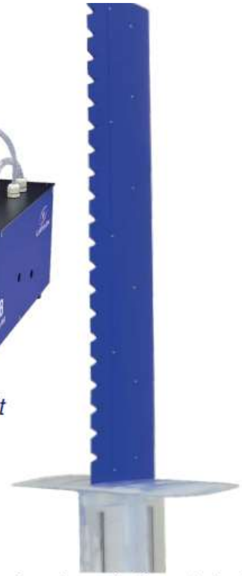
- TiO_2 (keep dry, agglomeration!)
- Aerosil 2000 (SiO_2, very small density)



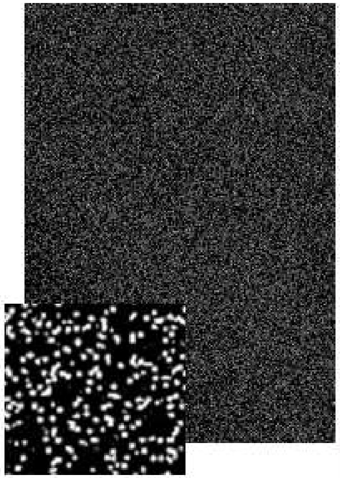
Large-scale Volumetric measurements with Helium-filled soap bubbles

- Air seeding with µm-particles is not suitable for large scale PIV/PTV experiments due to their limited scattering power.
- Neutrally buoyant Helium-filled Soap Bubbles (HFSB) with a diameter of 0.3 mm and a response time less than 15 µs and scatter 10000x more light than µm-particles.
- HFSB-Generator can deliver at a production rate of 40000 bubbles per second and per nozzle

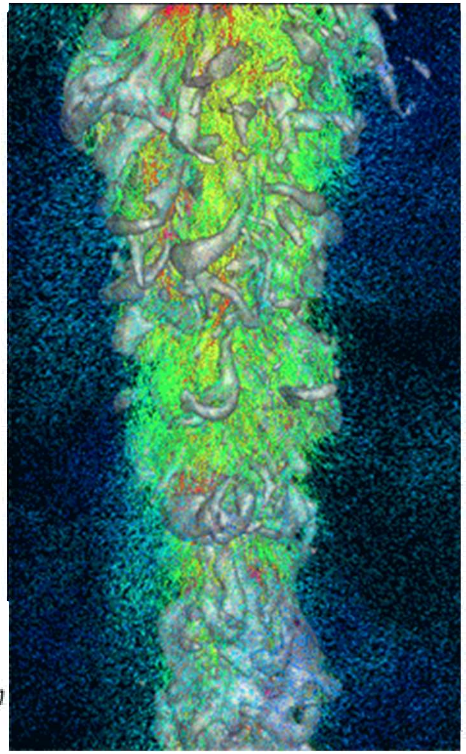
Fluid Supply Unit


Aerodynamically optimized HFSB linear nozzle array

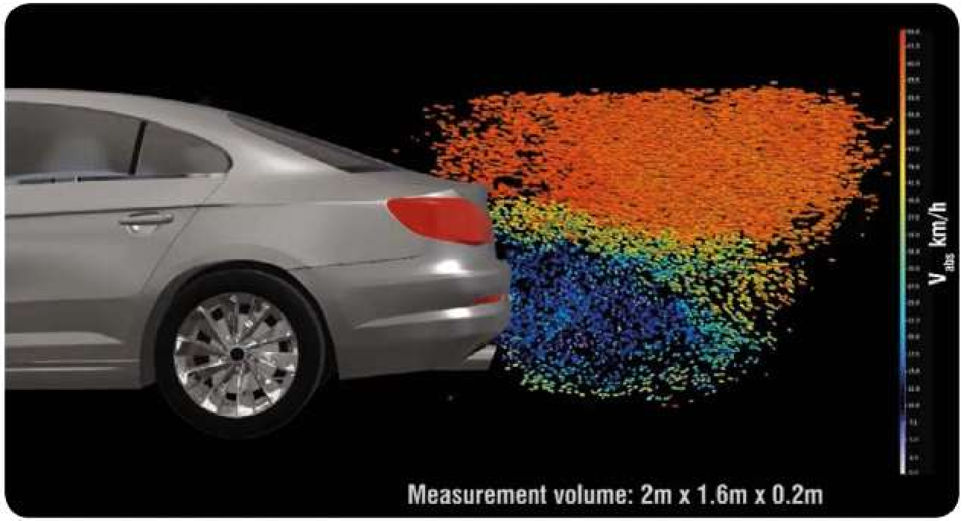
Example


Volume: 800 x 800 x 1200 mm³, illuminated with LED spots

Thermal air convection in 1 cubic meter



Particle tracks and vorticity contours calculated with Shake-the-Box (STB), courtesy D. Schanz, A. Schröder, F. Huhn DLR Göttingen

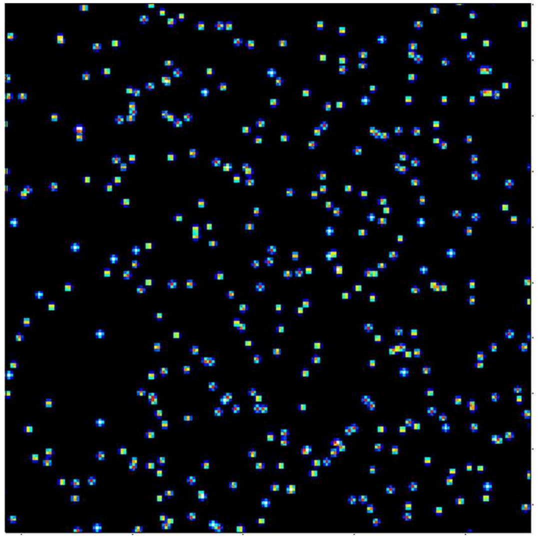


Measurement volume: 2m x 1.6m x 0.2m

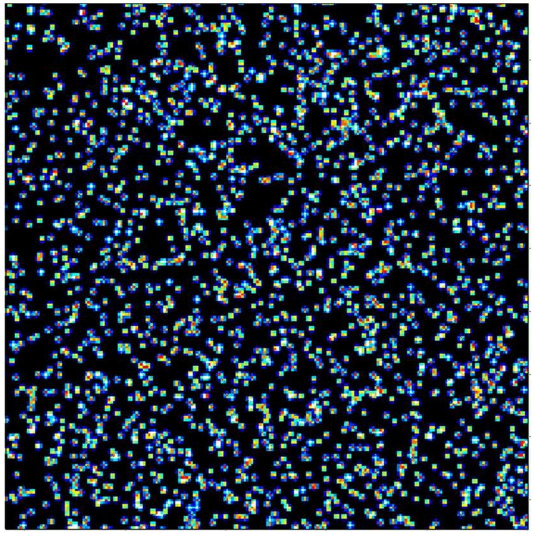
Measurement in the wake of a full-scale Volkswagen Sedan (courtesy VW)

Particle Density

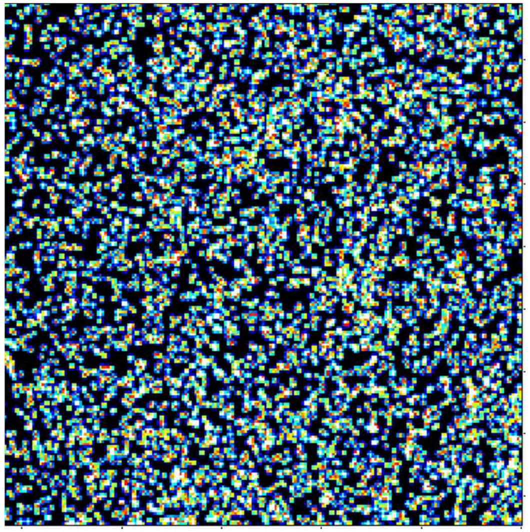
0.01 ppp



0.05 ppp



0.125 ppp

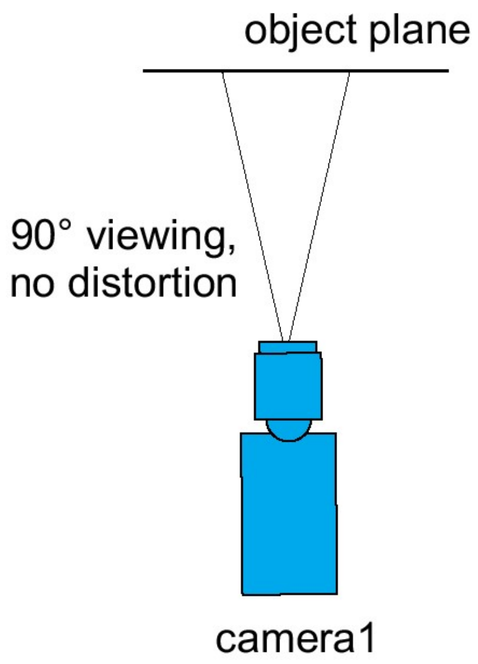


Calibration

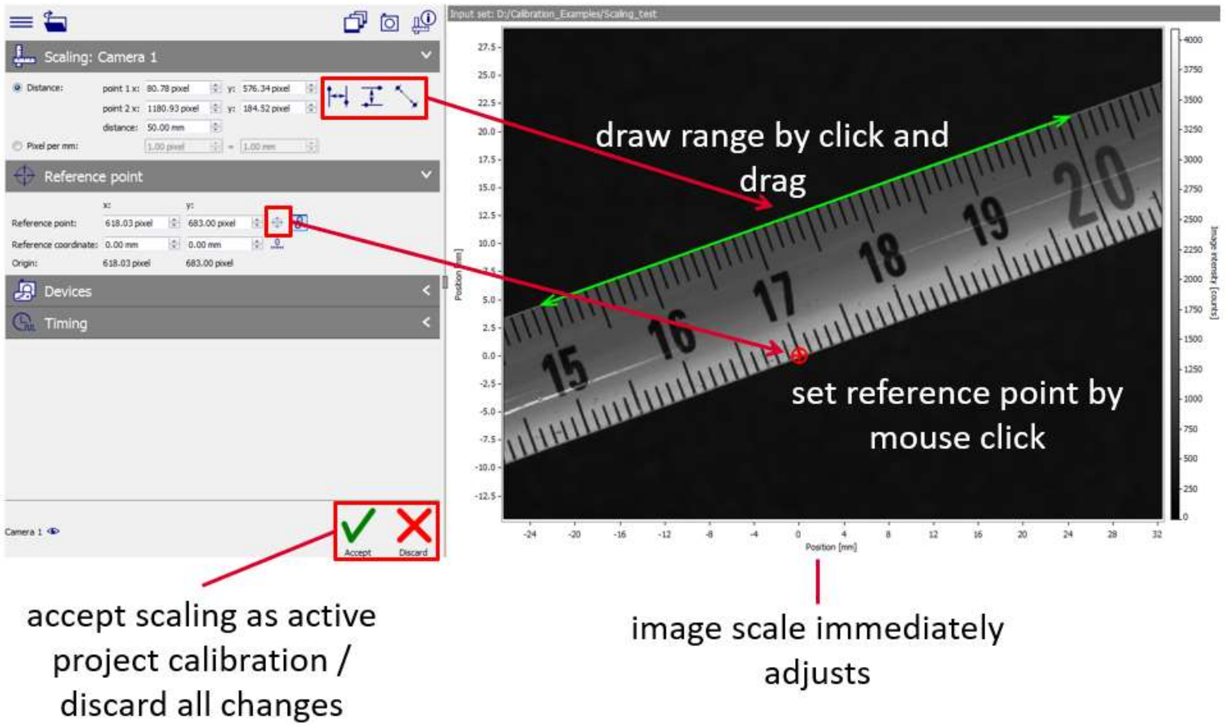
1. Scaling

Requirements:

- camera viewing direction is perpendicular to light sheet
- no image distortion (curved window etc.)
- linear camera lens (no fisheye, endoscope, etc.)



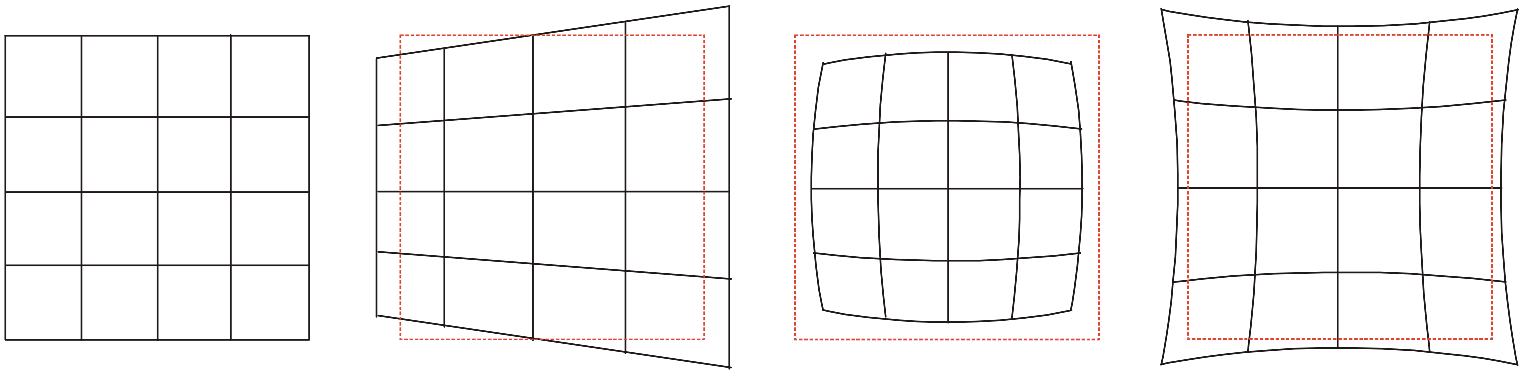
- load/acquire an image that includes two positions with known separation
  - specify these positions and their separation in **mm**



Nonlinear image correction

Reasons for image calibration:

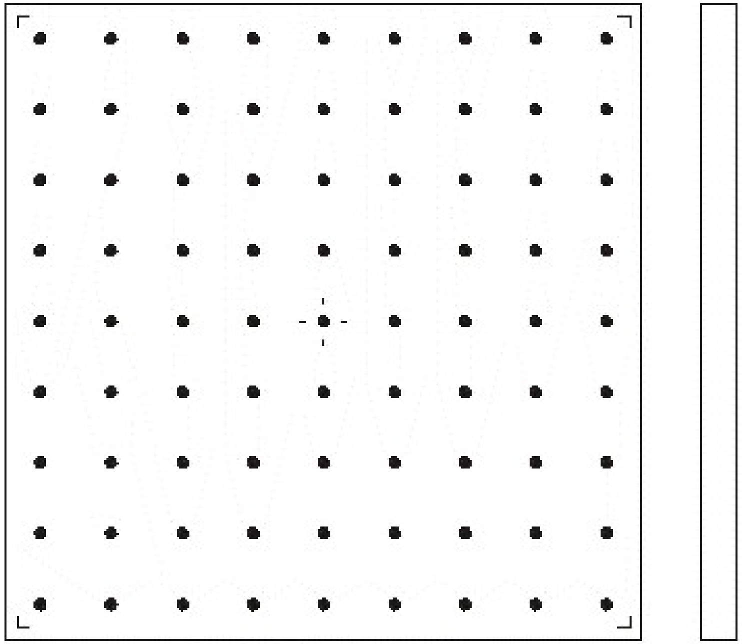
- oblique viewing direction
- distortion by curved windows (cylinder rings etc.)
- distortion by special camera lenses (fish eye, endoscopes)



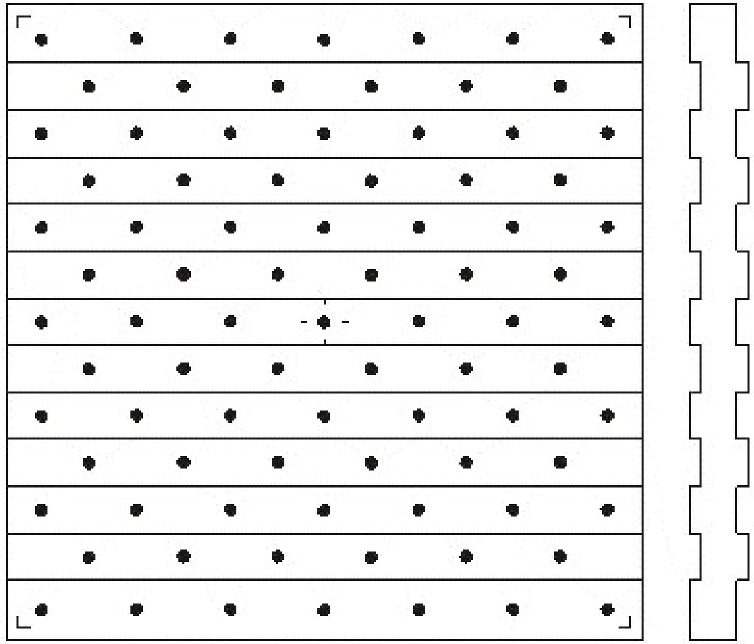
no distortion — oblique viewing distortion — barrel distortion — cushion

When using an angular separation stereo configuration its is necessary to establish a non linear mapping function between the measurement volume and position on the sensor.

Calibration: calibration plates



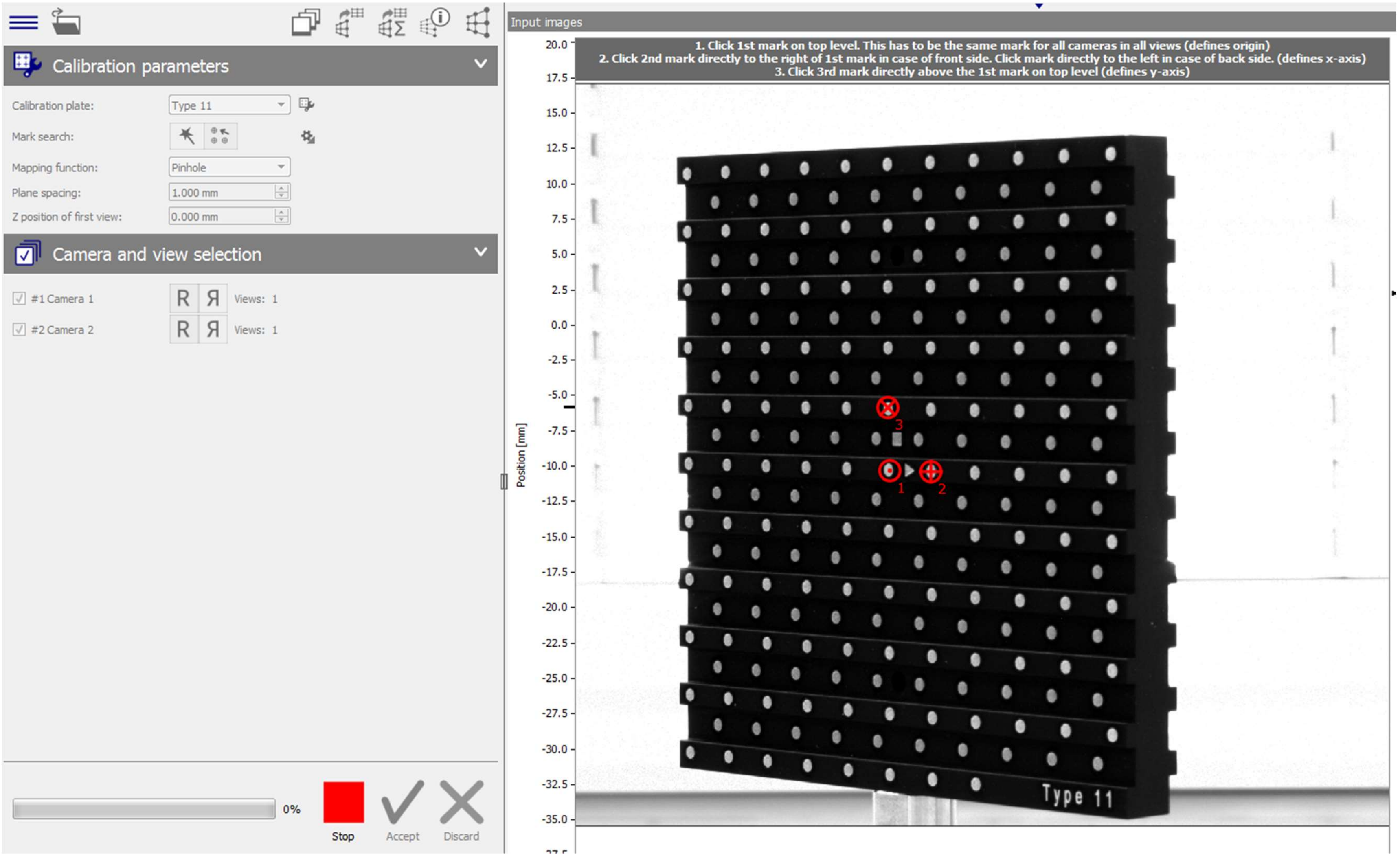
flat calibration plate



two-level calibration plate

Calibration plates are available in different dimensions

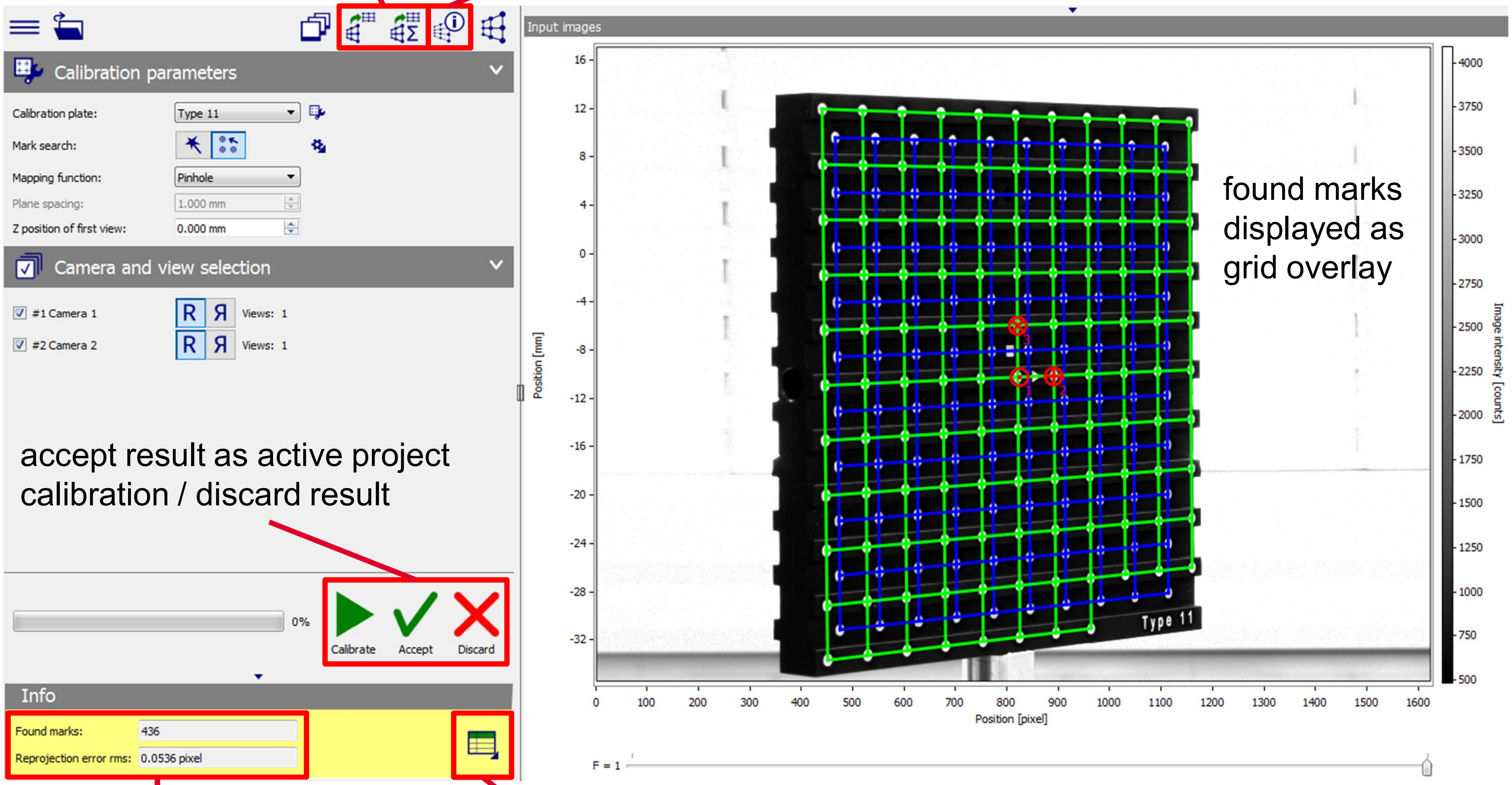
3D Calibration procedure



Calibration: result and evaluation

show corrected images

show detailed calibration result



found marks displayed as grid overlay

accept result as active project calibration / discard result

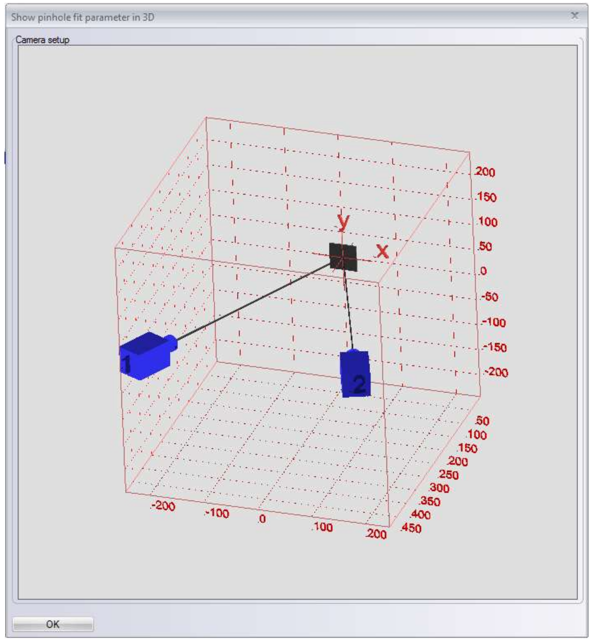
short summary of found marks and reprojection error

show found marks and reprojection error for each view and camera

How to choose: polynomial vs. pinhole

Only perspective distortion (e.g. no diffraction in glass window/pipe) → pinhole model

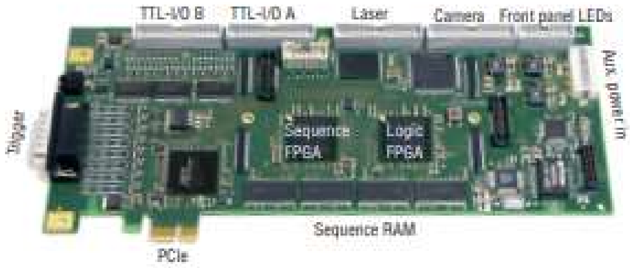
- Benefit: physically meaningful parameters
- Calibration plate *does not need* to cover full camera image (extrapolates well)



Arbitrary distortions (windows, pipes)→ polynomial mapping

- Very poor extrapolation
- Calibration plate ***must*** cover full camera image

Synchronization



- fully synchronized recording with a precision better than 50 ps

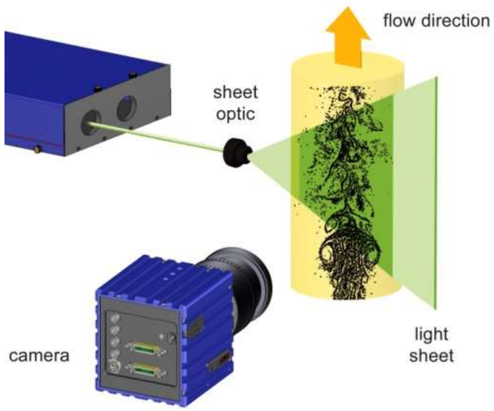
Specifications		
	Sequencer output lines	up to 24 independent
	Inputs	trigger, start, phase, 4x TTL-in
	Output drivers	TTL 50 Ω
	Input load	TTL 50 Ω or „high-Z“, software selectable
	Output precision	typ. 50 ps
	Processor	dual-FPGA for firmware and sequencer
	Sequence RAM	64 MByte

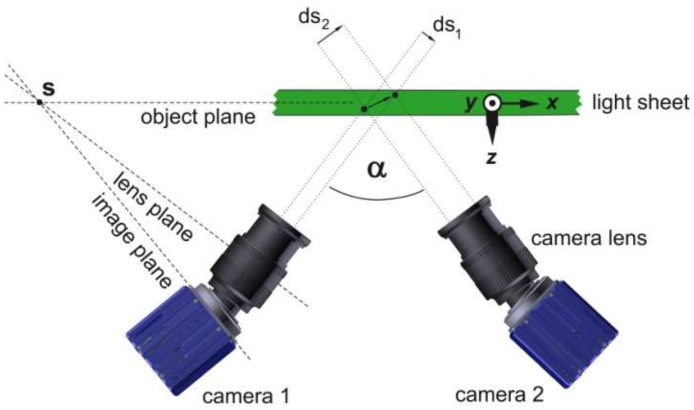
Advanced Techniques

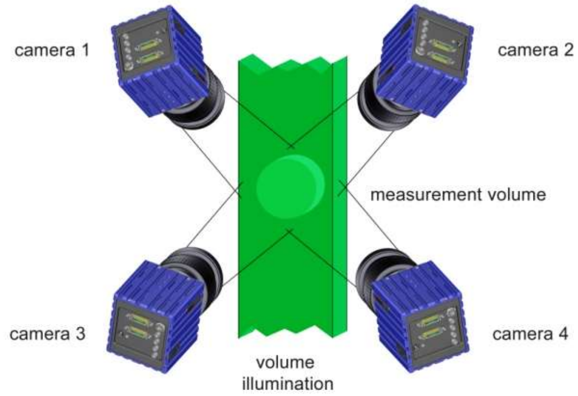
- Stereo PIV
- Tomo PIV
- Time Resolved PIV (TRPIV)
- MicroPIV (2D/Stereo/Tomo)
- Thermographic PIV
- Fluid Structure Interaction (FSI)
- STB
- Underwater PIV
- Endoscopic PIV

PIV: Multi-Dimensional Flow Field Imaging

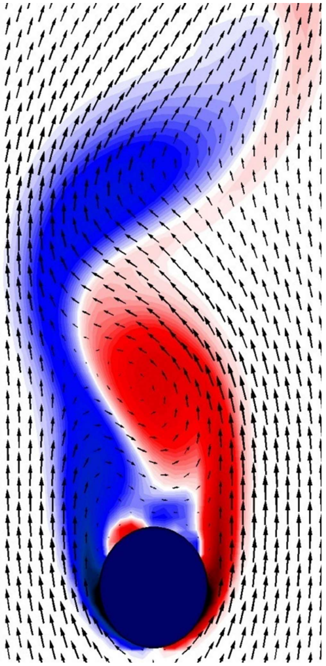
2D-PIV 2D2C	Stereo-PIV 2D3C	Volume (Tomo) PIV 3D3C



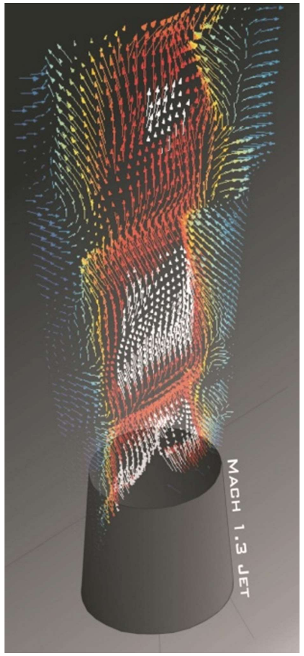




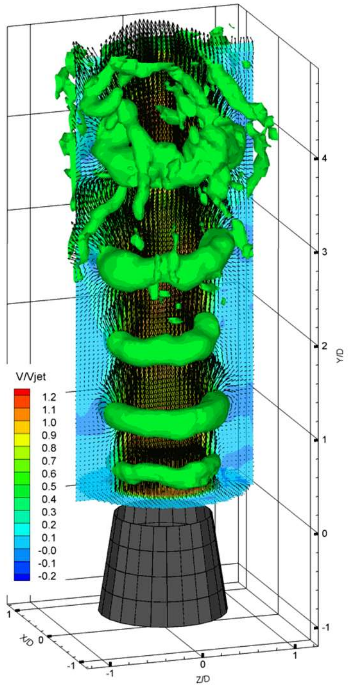
x, y
v_x, v_y



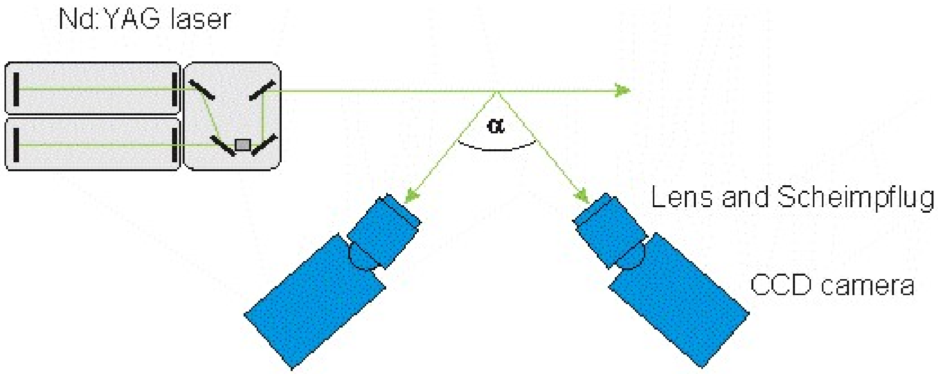
x, y
v_x, v_y, v_z



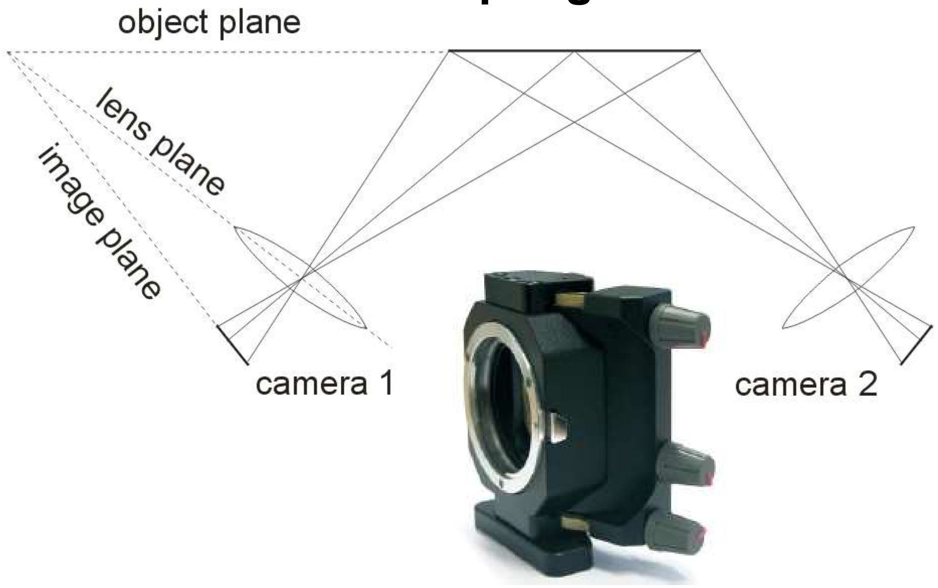
x, y, z
v_x, v_y, v_z



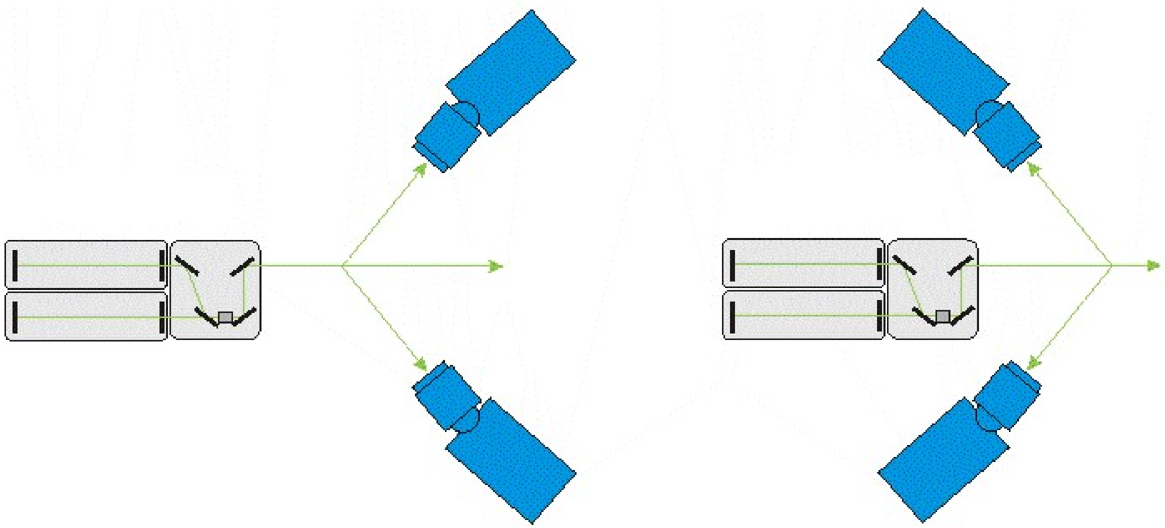
Stereo PIV: Possible Arrangements



Scheimpflug condition

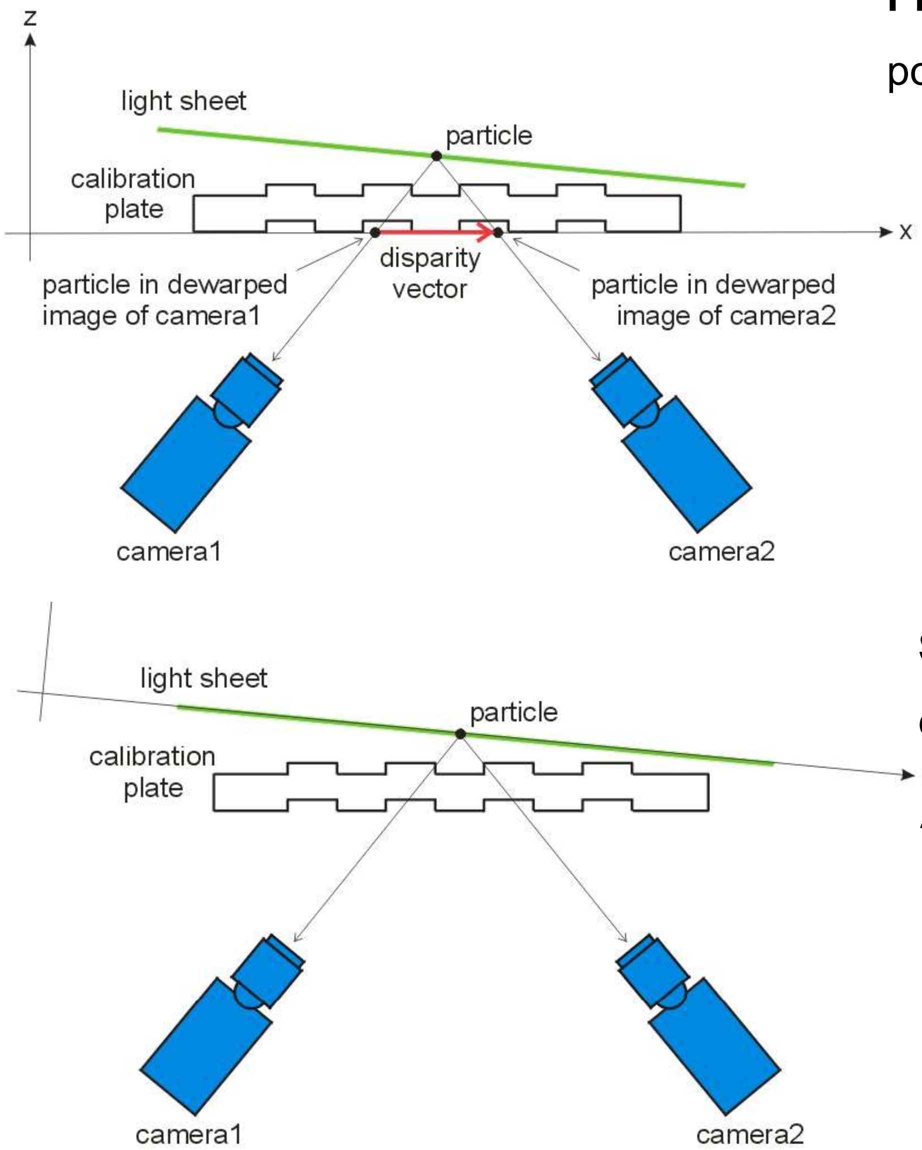


- both cameras on one side of the light sheet
- different intensities (→Mie scattering)



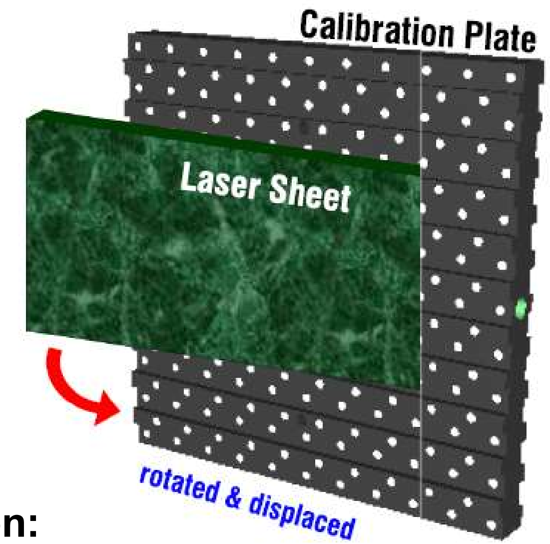
- cameras on different sides of the light sheet (→same intensities)
- transparent calibration plate needed

Stereo PIV: Self Calibration (Patented)



Problem:

position of calibration plate ≠ position of light sheet



Solution:

calibration correction by particle images

Advantages:

- reduction of calibration errors
- calibration plate can be outside of measurement volume
- side benefit: position and thickness of laser sheet is measured

Reference: Wieneke B (2005), “Stereo-PIV using self-calibration on particle images“, Exp Fluids, Vol. 39, 267–280

2D PIV: Hummingbird

Application
Flow around hummingbirds

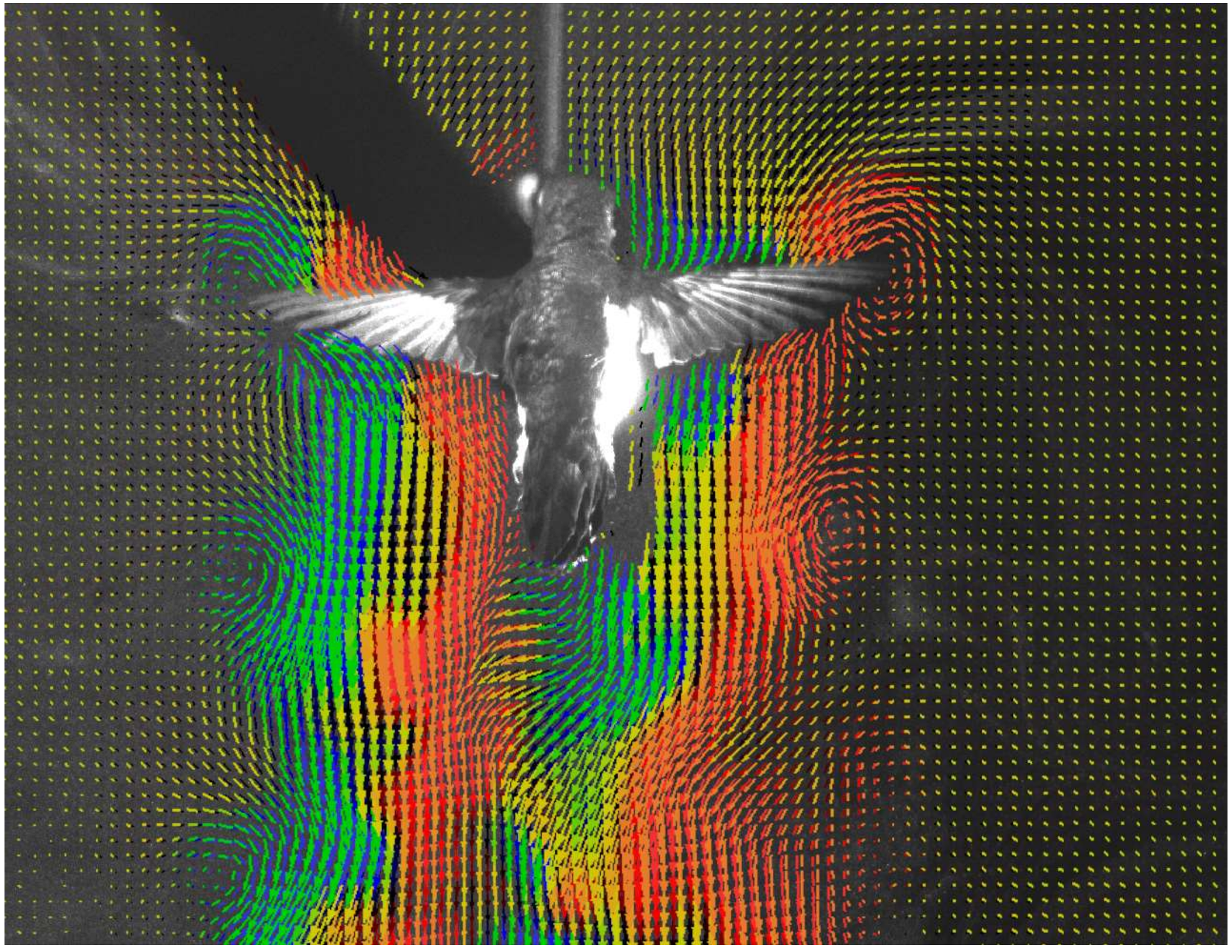
Field of View
100 x 75 mm

Equipment
Imager Intense
Solo III lasers

Seeding
Atomized olive oil

PIV Parameters
Double frame/double exp.
Mulitpass (64 x 64; 32 x 32)
50% overlap

LaVision Ref: SA 04/03



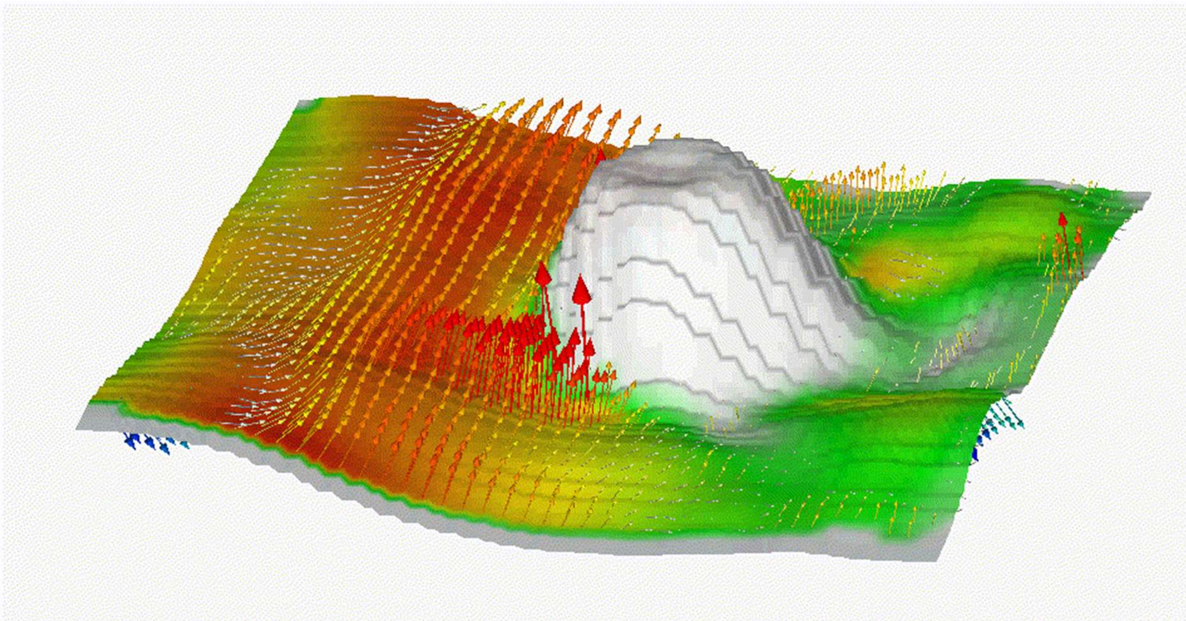
Stereo PIV on Surfaces: Surface Waves

Stereo PIV

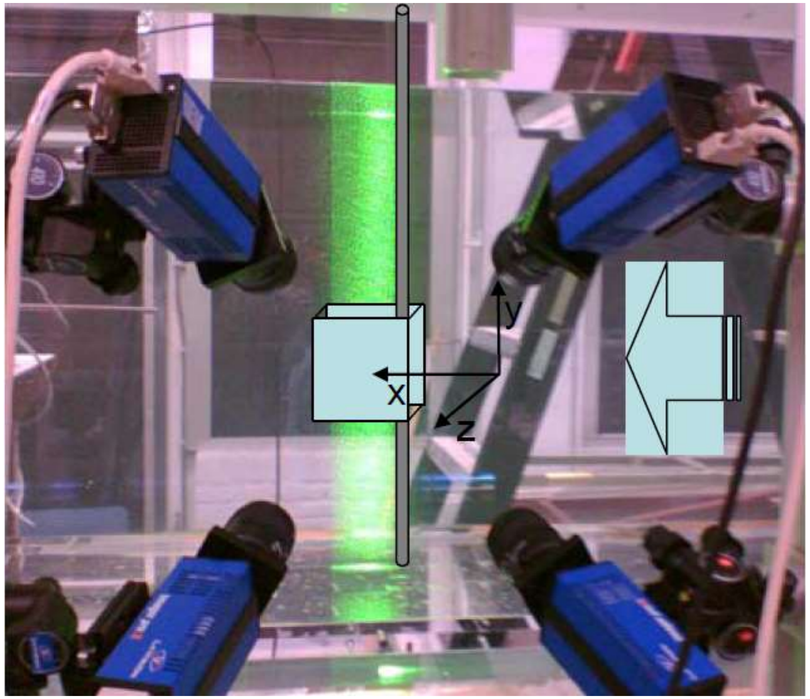
- articles floating on surface
- white light illumination

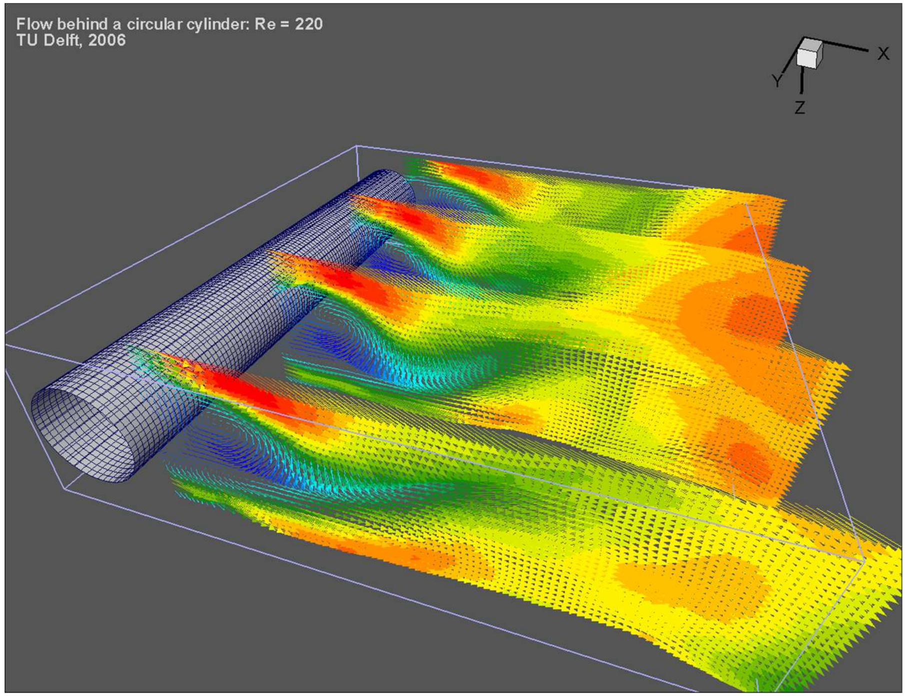
3D surface shape and motion

- water waves with obstacle



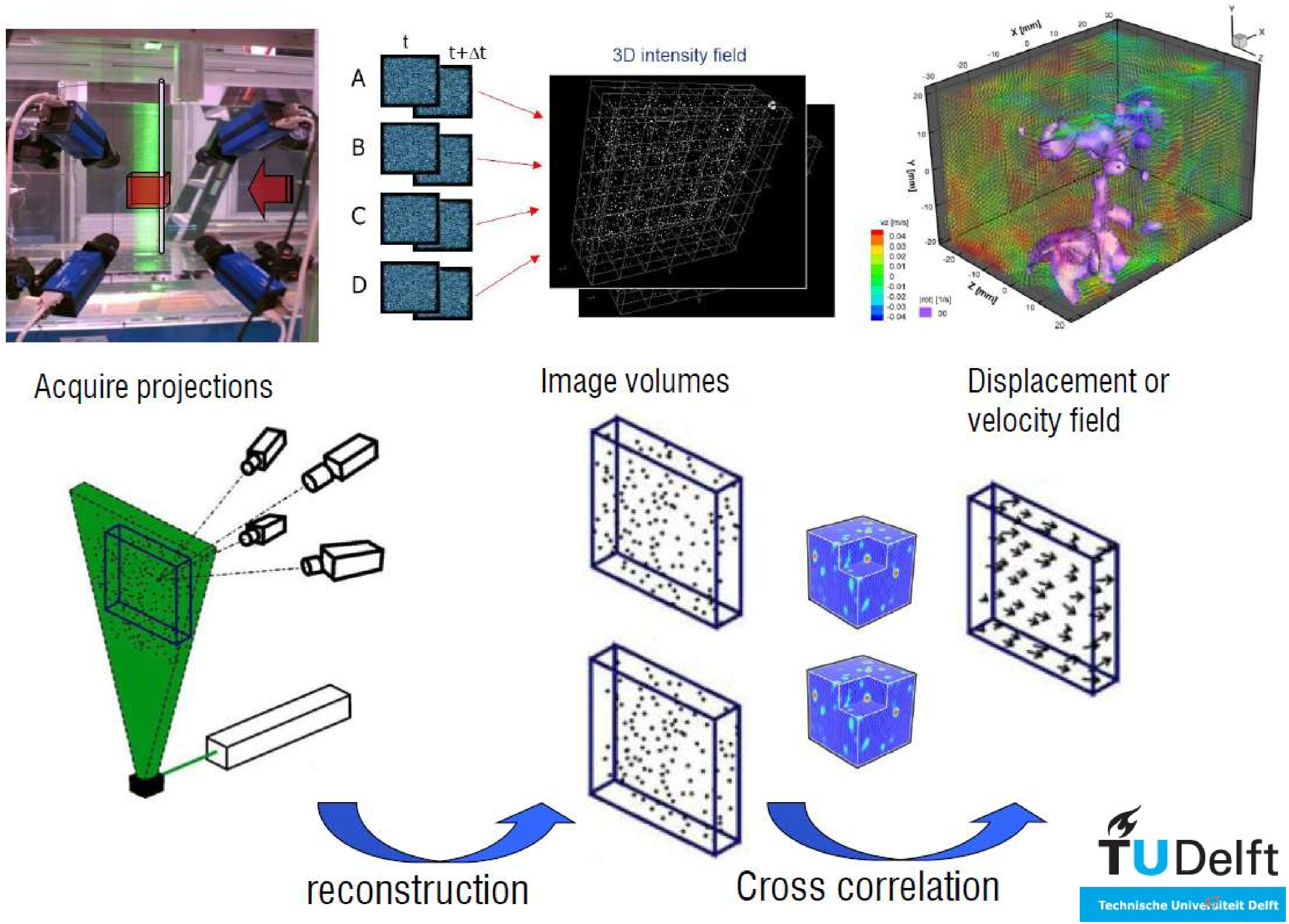
plane color = u-velocity component,
vector color = w-velocity component
vertical axis enlarged



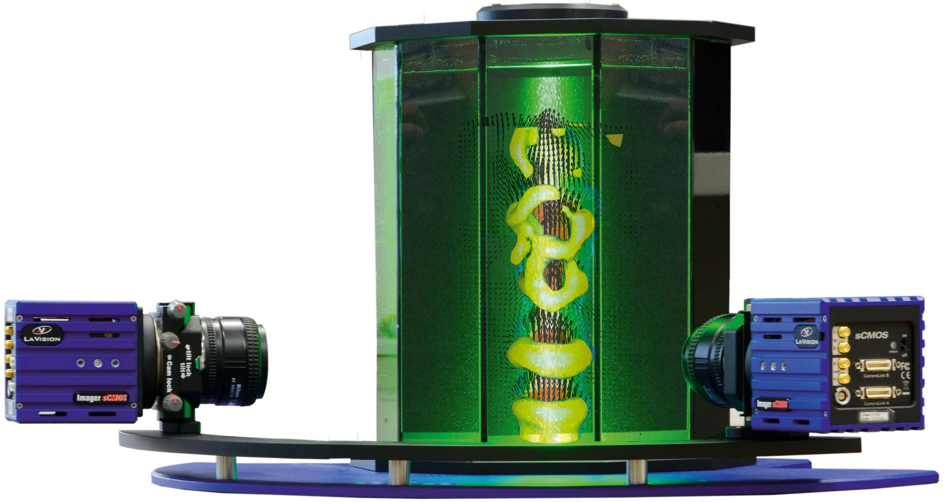


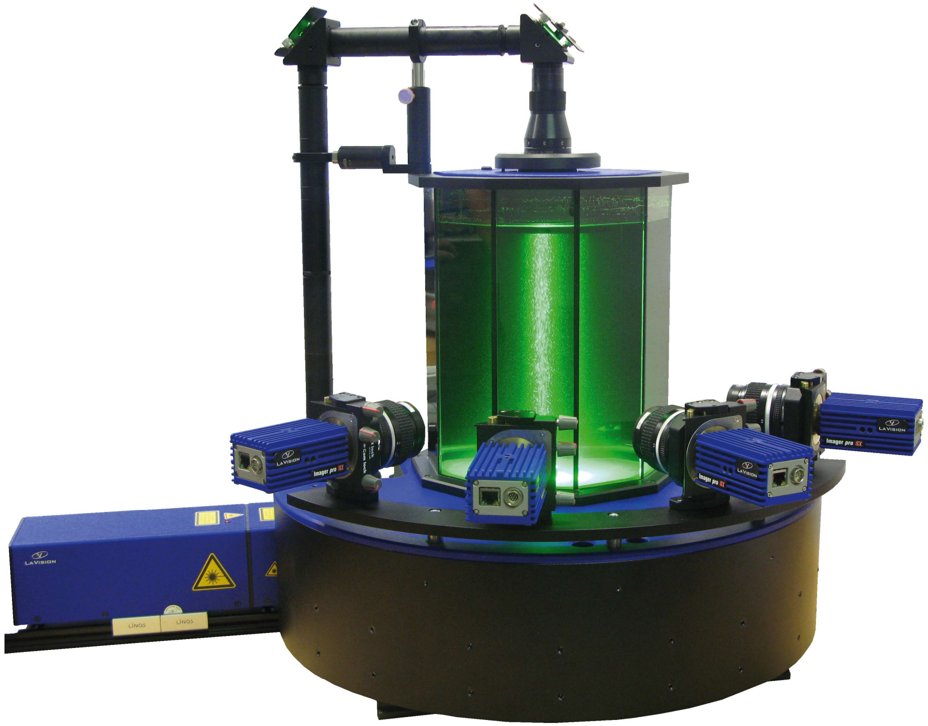
True 3-Dimensional PIV= Tomo-PIV

Volume PIV (3D3C) : Tomographic-PIV

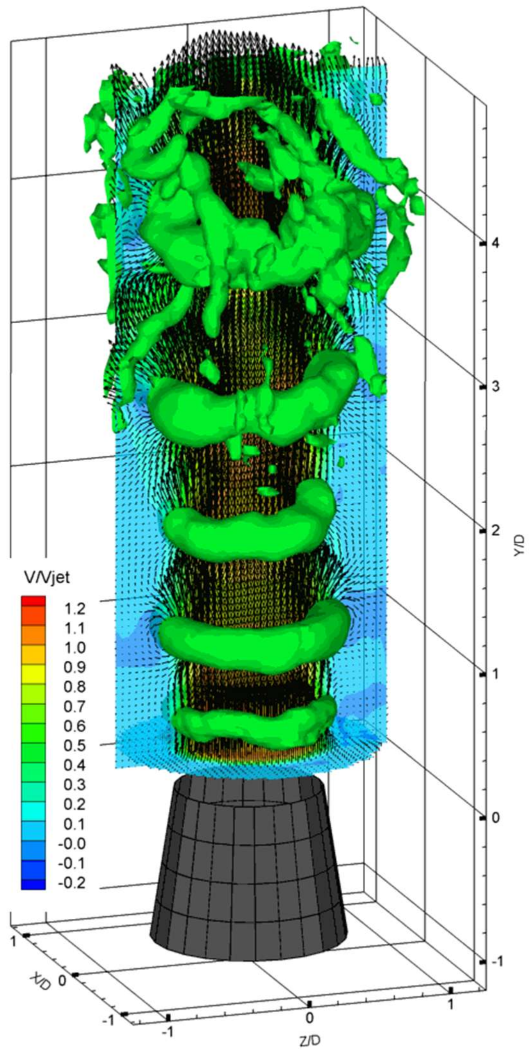


Tomo-PIV: 2 – 4 Cameras



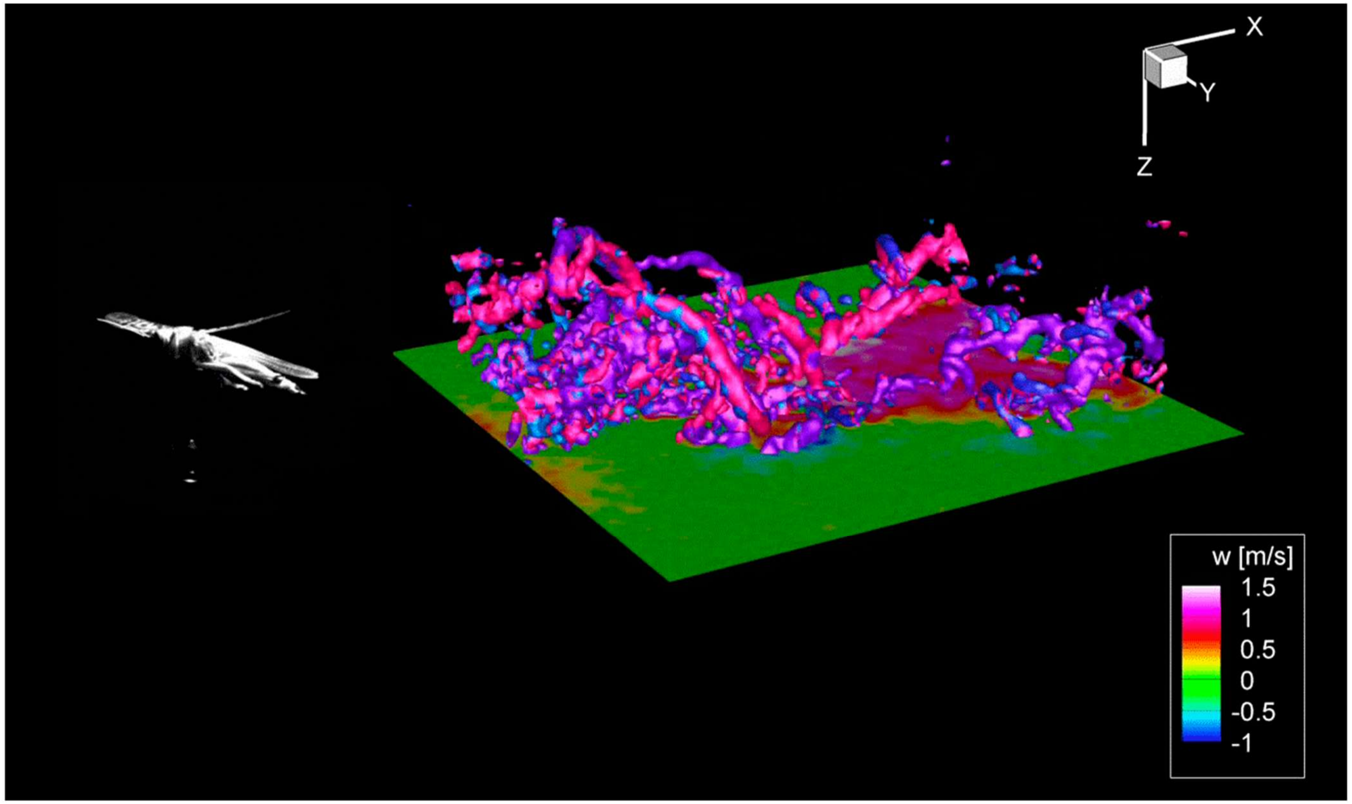


Jet in Water

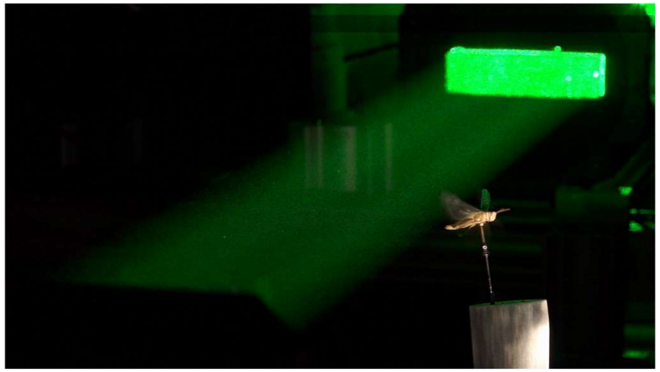


reconstructed volume:
60 x 65 x 65 mm^3

Tomo-PIV: Locust Wake



Time-resolved Tomo-PIV measurements in the wake flow of a locust flying in a wind tunnel

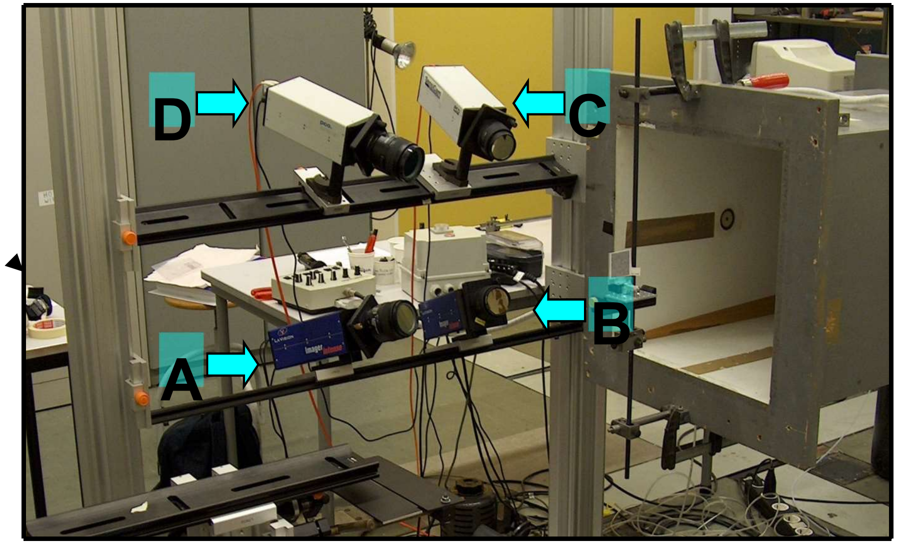


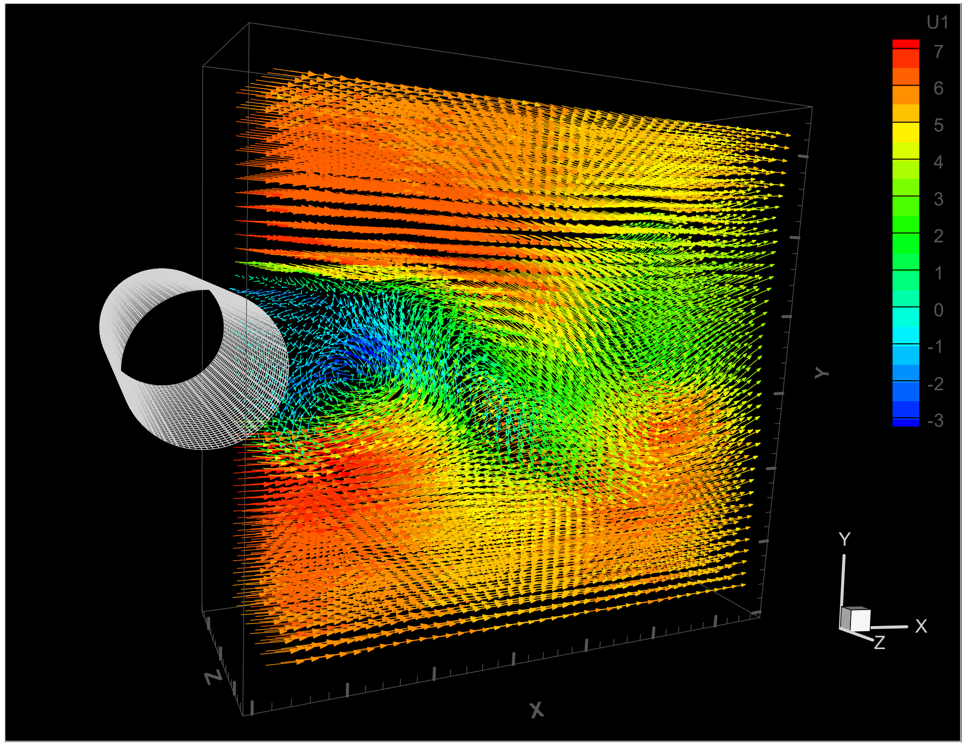
courtesy: R. Bomphrey, Dept. of Zoology, University of Oxford

Tomo-PIV on cylinder wake

Experimental apparatus: wind tunnel, illumination, imaging

- low-speed wind tunnel: V_∞ = 5 m/s
- circular cylinder: D = 8 mm (Re_D = 2800)
- camera: 4x 1376x1040 pixel, 12 bit
- laser: 400 mJ/pulse f# = 8-11





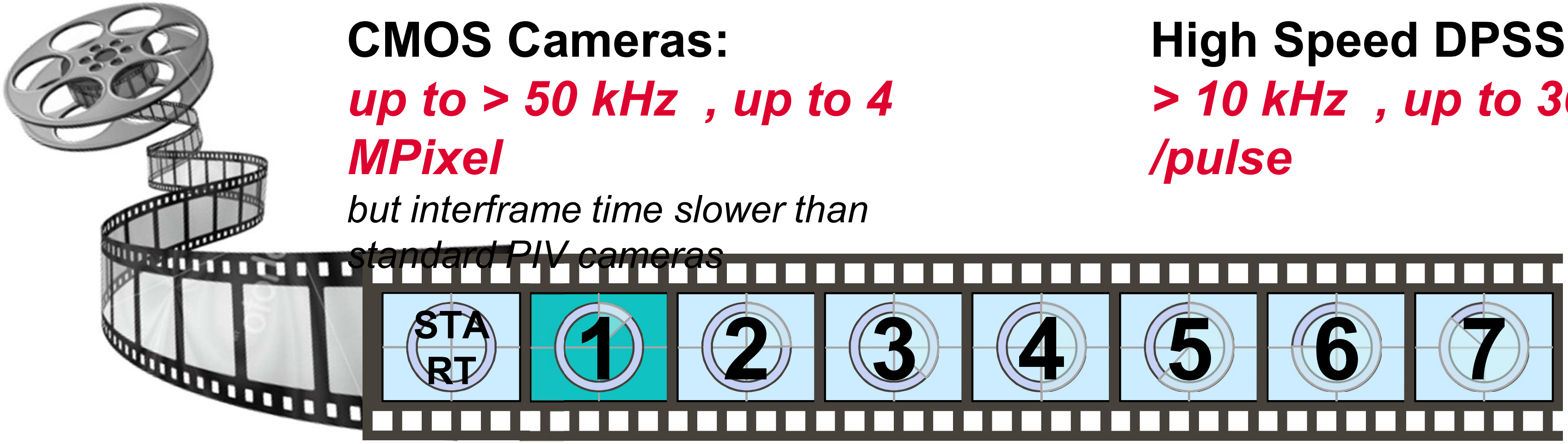
FOV: 40 x 40 x 8 mm
= 730 x 731 x 184 voxel

Interrogation volumes:
41 x 41 x 21 voxel
75% overlap

Number of vectors:
64 x 64 x 30
= 122.000

Estimated accuracy:
~ 0.05 pixel

Time Resolved PIV



CMOS Cameras:

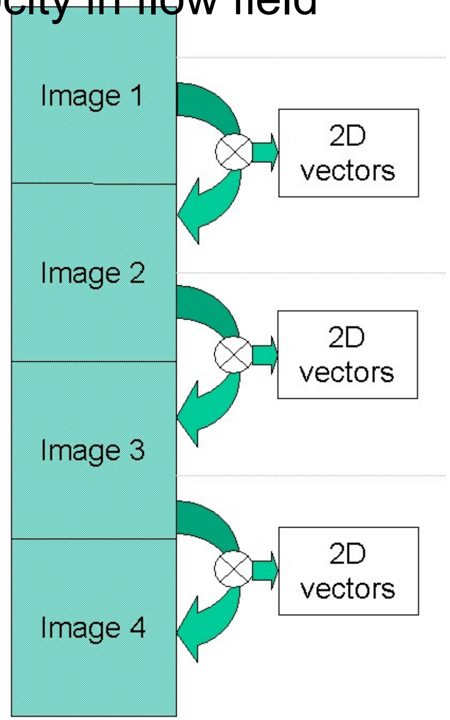
up to > 50 kHz , up to 4 MPixel

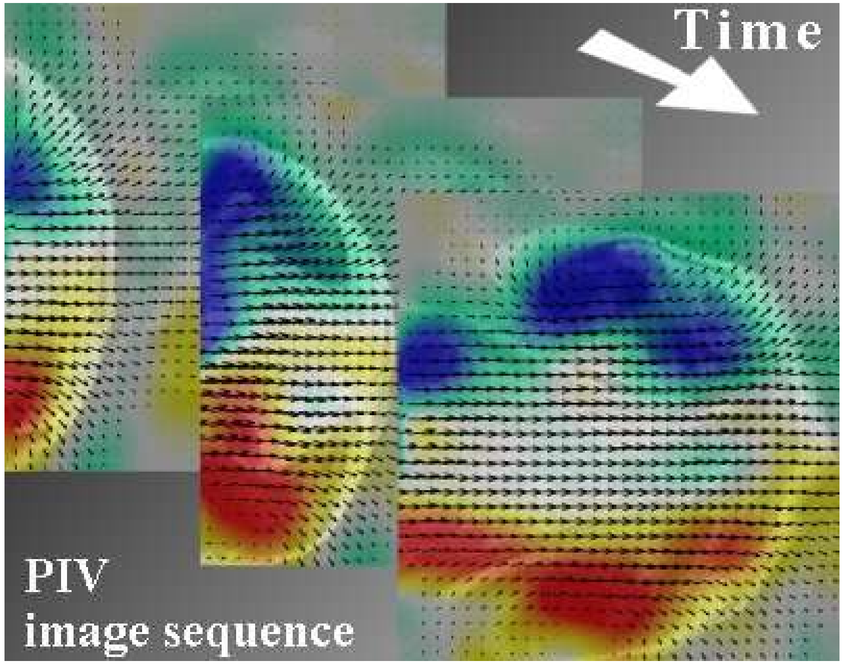
but interframe time slower than standard PIV cameras

High Speed DPSS Laser:

> 10 kHz , up to 30 mJ /pulse

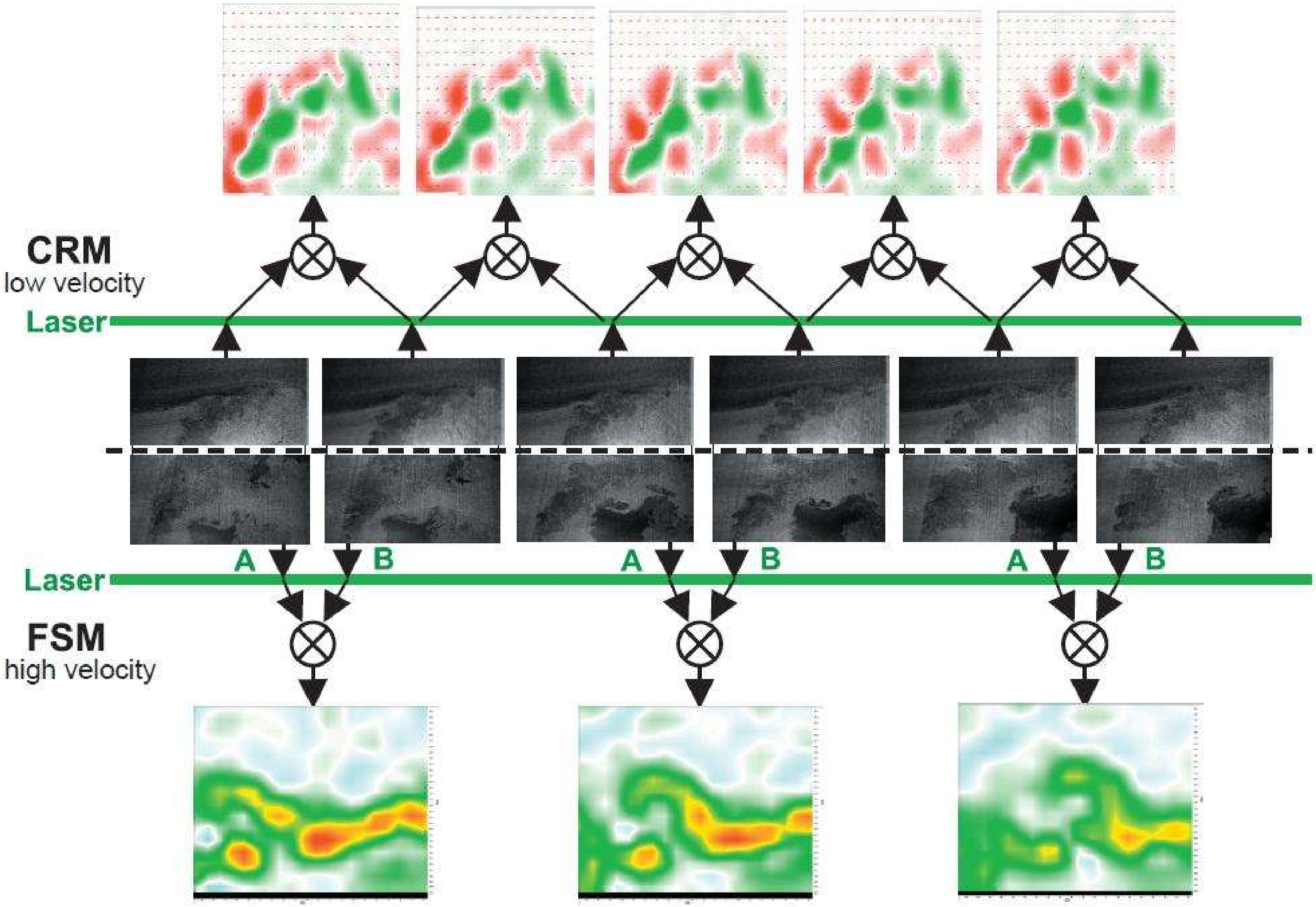
Note: "high speed" image recording means high frame rate **NOT** high velocity in flow field

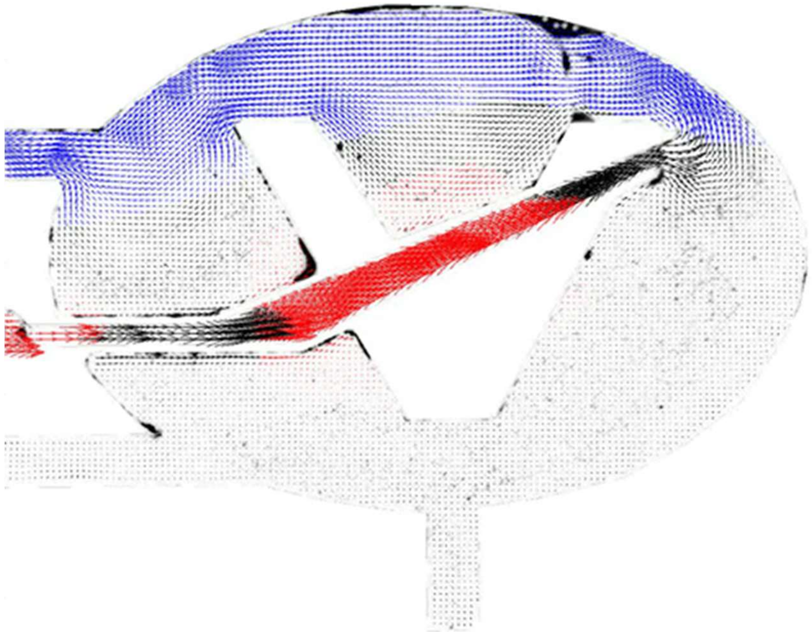




Time Resolved PIV: Different Operating Modes

CRM: Constant Rate Mode
FSM: Frame Straddling Mode



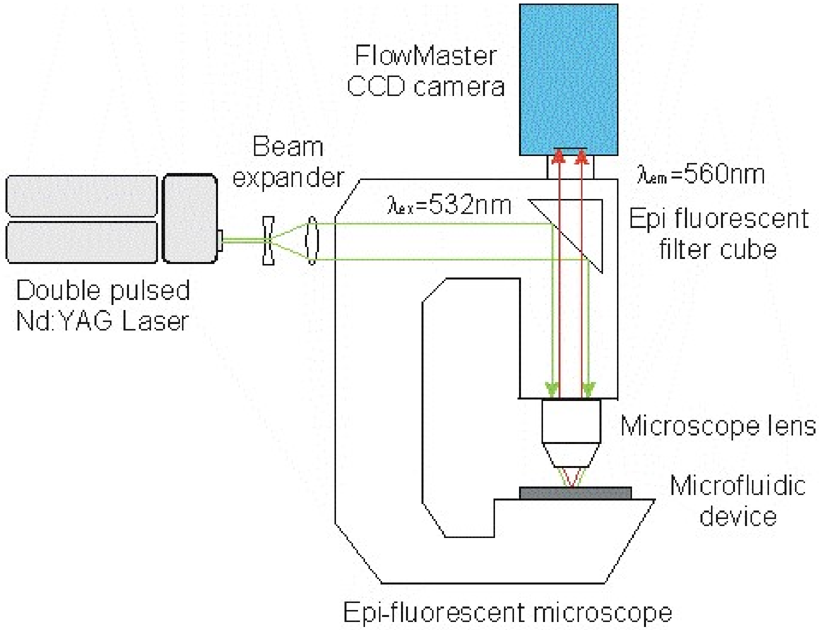


Microscopic PIV with fluorescent particles in volume illumination

Microscopic PIV = Micro-PIV = µPIV

PIV with microscopic resolution for

- micro channel flow applications
- micro electromechanical systems
- bio-analytical devices



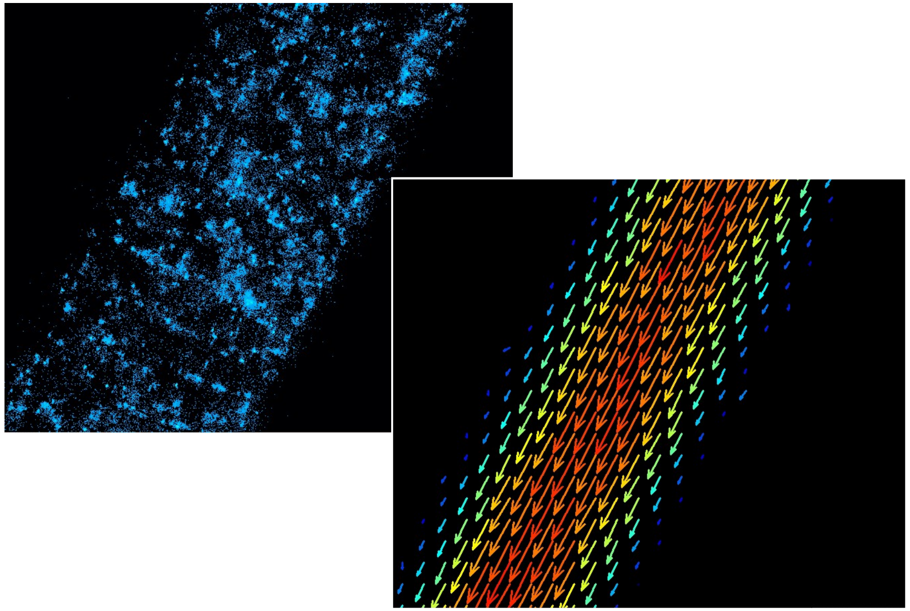
µPIV setup

	Standard PIV	Micro-PIV
Illumination volume	light sheet	
Techniques	Mie (or LIF)	LIF
Line-of-Sight Resolution	thickness of light sheet (≥ 100 µm)	focal depth of microscope lens (≥ 2 µm)

Examples of MicroPIV

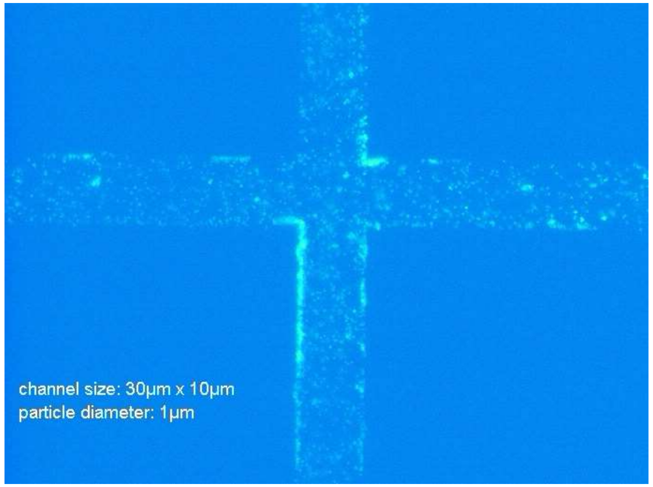
on microchannel of 200 µm width

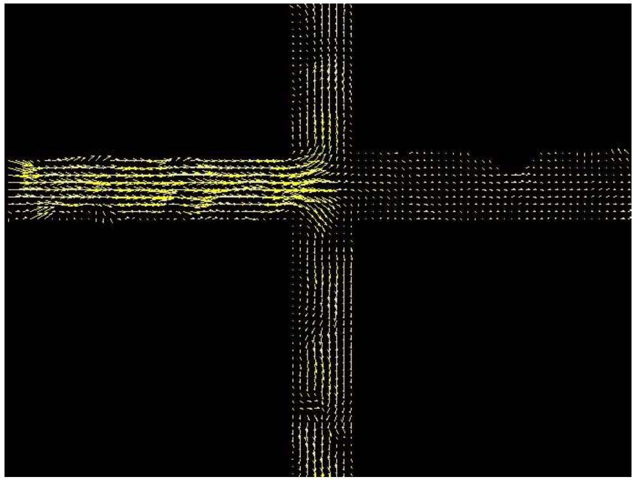
- **10x magnification**
- **seeded with 1 µm particles**



on microchannel of 30 µm width

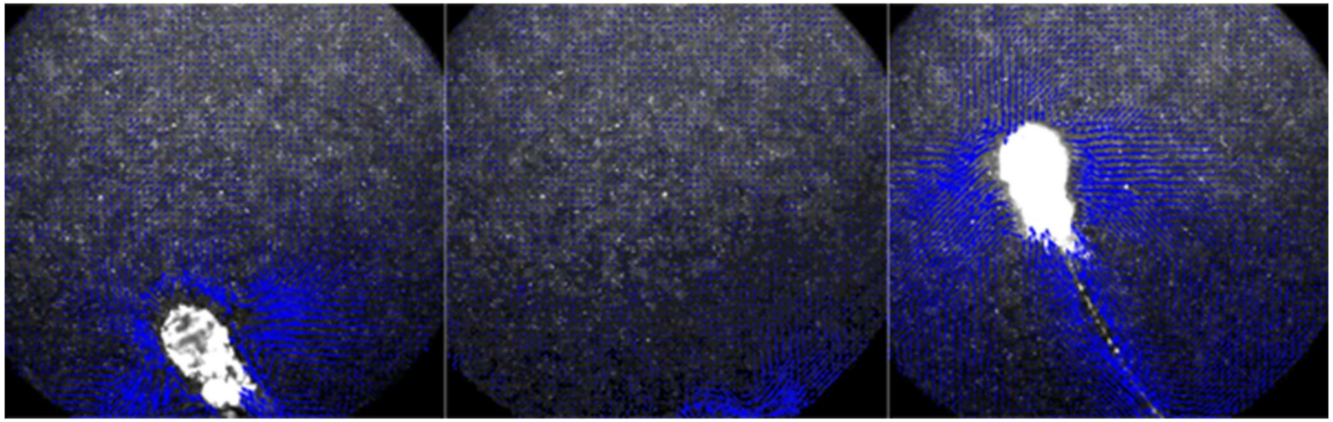
- **40x magnification**
- **seeded with 1 µm particles**





Stereo / Volumetric µ-PIV

Flow field around a moving 100 µm plankton recorded at 1 kHz frame rate using StereoMicroPIV



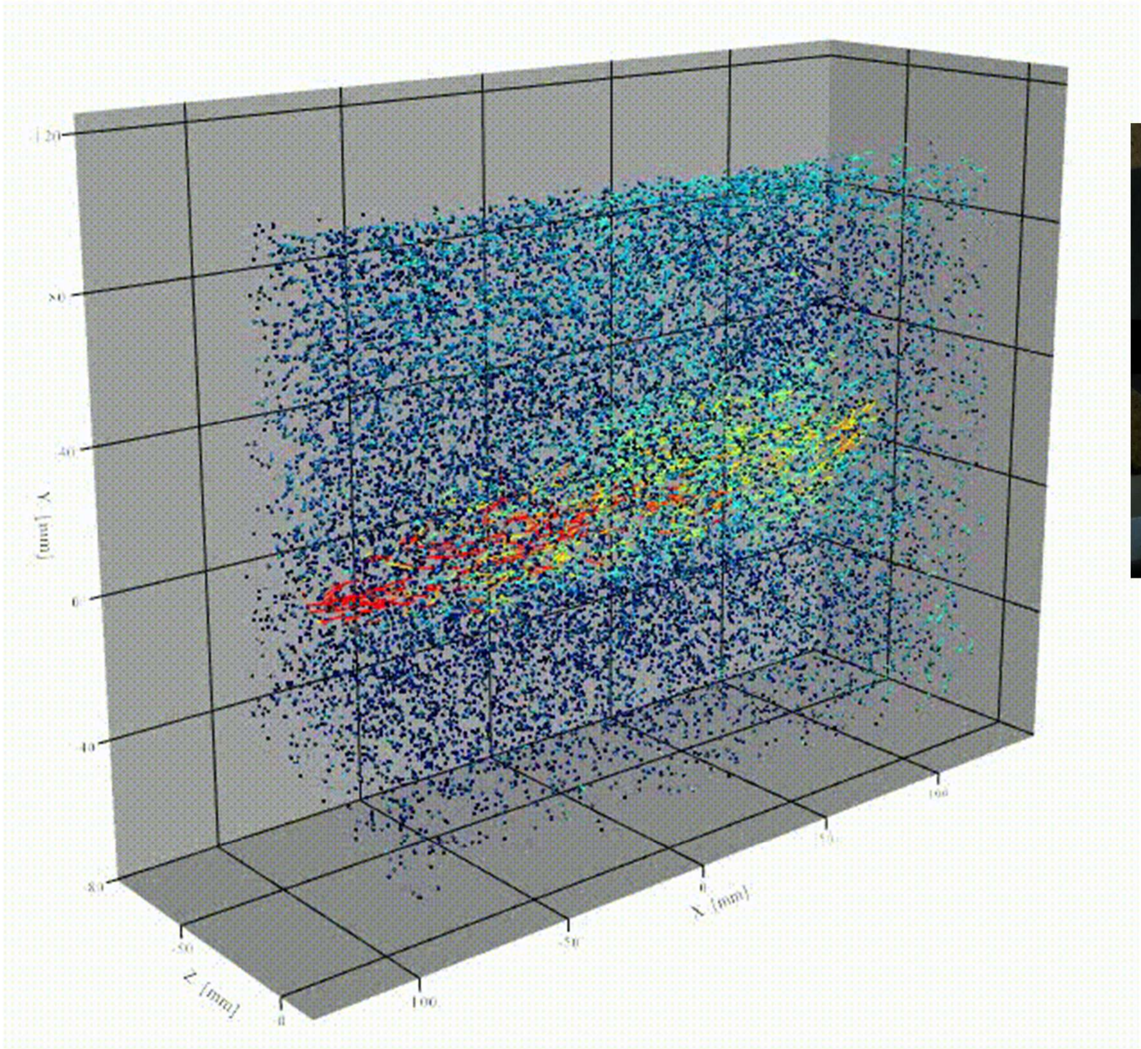
Motorized options for both Inverted Microscope and Stereo Microscope

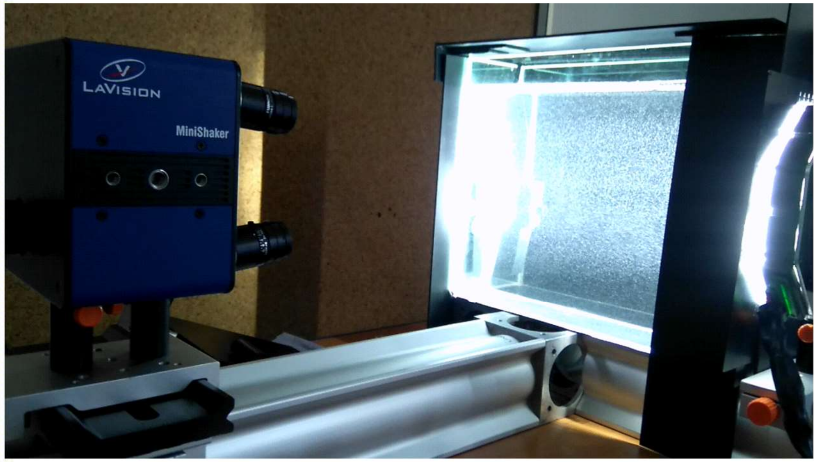
Motorized Inverted Microscope

Motorized Stereo Microscope

Shake-The-Box (STB)

- **Shake-the-Box** is the most advanced 3D Lagrangian Particle Tracking Velocimetry (PTV) method for densely seeded flows at highest spatial resolution.
- **Shake-the-Box** is a purely particle-based technique using an Iterative Particle Reconstruction (IPR) technique in combination with an advanced 4D-PTV algorithm using the





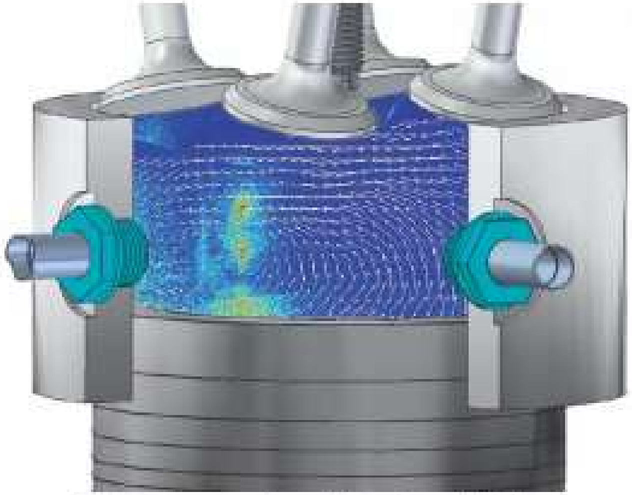
- ✓ **Sensor size:** 4 x 896 x 656 px, 4 x 0.53 Mpx (full sensor: 2 Mpx each), 10 Bit
- ✓ **FOV:** *f* = 8mm, 23x16x15cm³
- ✓ **Repetition rate:** 500 Hz
- ✓ **Working distance:** 50 cm
- ✓ **Illumination: White** LED300

Endoscopic PIV

With endoscopic PIV, a costly manufacturing of prototypes with large windows for optical access can often be avoided. Instead, only 8 mm holes are needed for a PIV measurement of internal aerodynamic phenomena, reactive flow fields and combustion processes. Applications include:

- turbomachinery
- aircraft engines
- compressors
- pumps
- IC engines
- pharmaceutical and live science applications

Camera endoscope mounted to a FlowMaster series camera

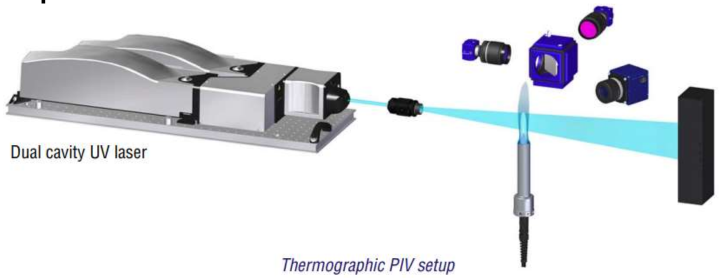


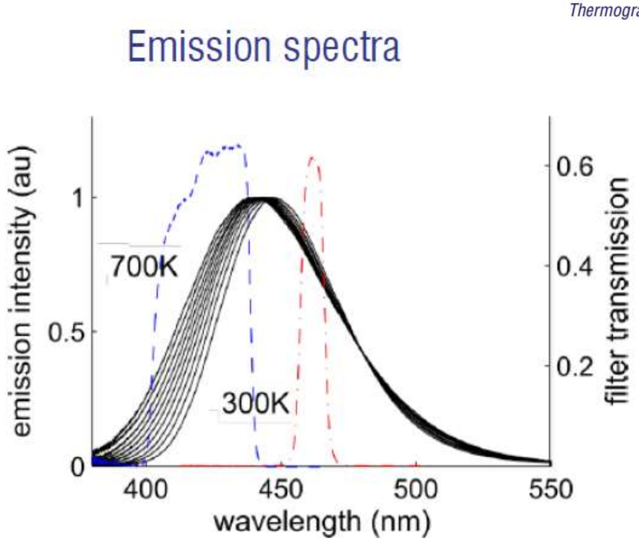
Instantaneous in-cylinder tumble flow, courtesy: Volkswagen

Laser endoscope forming a light sheet from a high power pulsed laser

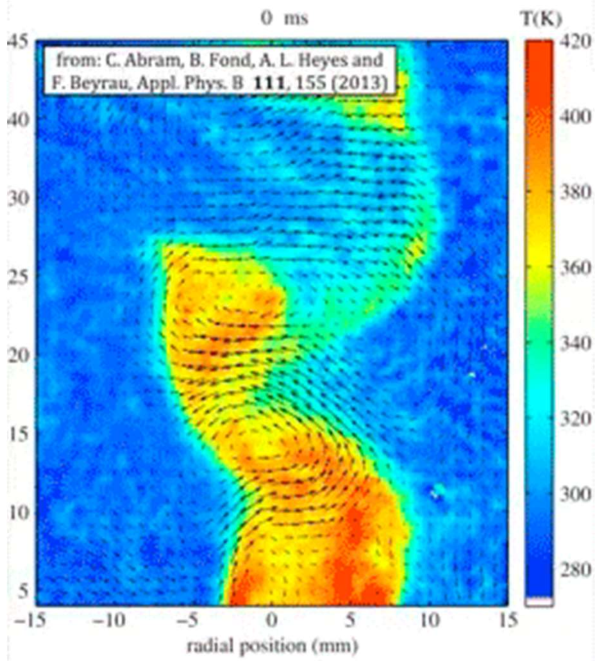
Thermographic PIV

- for simultaneous flow velocity and temperature measurements
- it works with phosphorescent PIV particles, which are suitable both for PIV and laser induced thermometry measurements with only slightly modified PIV systems.
- For PIV: use Mie UV Scattering and
- for Temperature: temperature sensitive emission after UV laser excitation which is used thermometry.





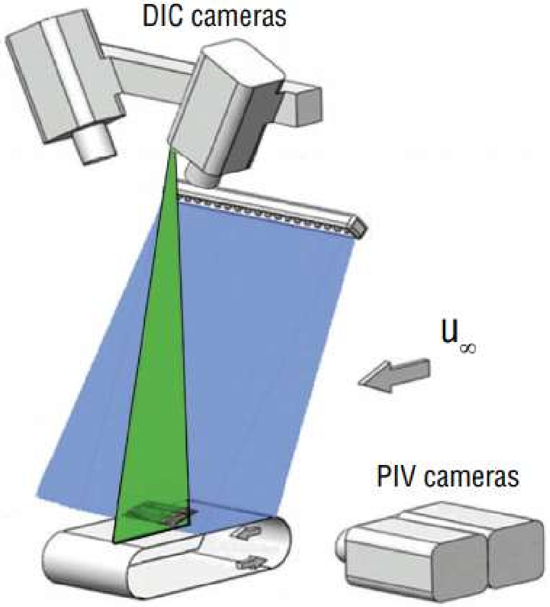
Example: BAM:Europium ($BaMgAl_{10}O_{17}:Eu^{2+}$)



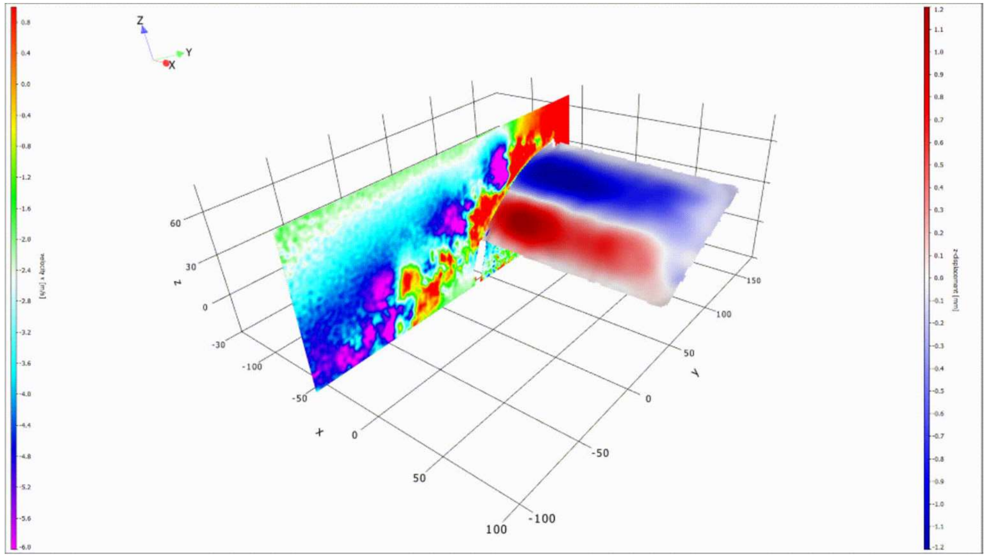
Simultaneous high speed imaging of flow & gas temperature fi of a BAM:Eu-particle seeded air flow

Fluid Structure Interaction (FSI)

Fluid-Structure Interaction (FSI) is the interaction occurring between a moving and/or deformable structure, and an internal or external flow.

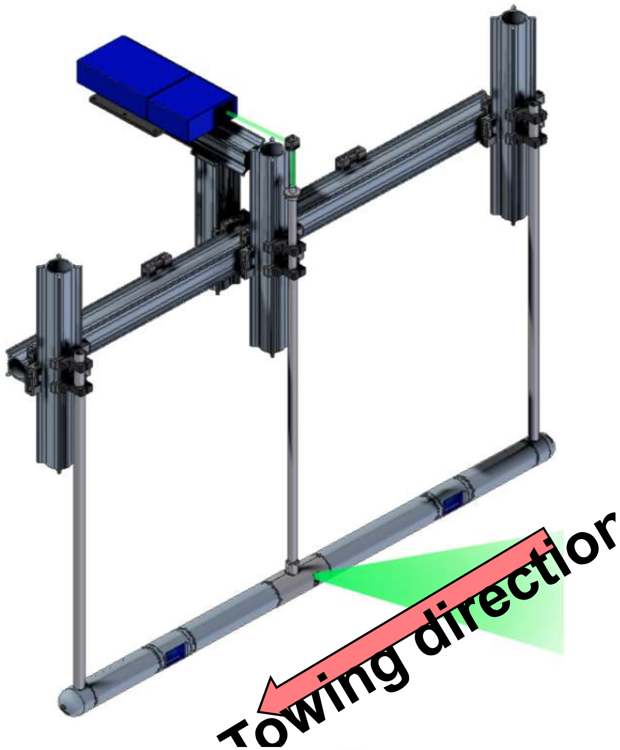


Setup: test wing above a rotating steel belt in a wind tunnel: LED and laser illumination from above, two PIV cameras recording from the side, two DIC cameras recording from the top, courtesy of R. Bleischwitz et al., Southampton University[27]



Underwater PIV

- Underwater measurements in towing tanks, cavitation tunnels, or offshore facilities imply extraordinary challenges for the experimentalist and his equipment.
- The modular concept of LaVision’s **FlowMaster Underwater PIV** systems allows a large variety of PIV imaging configurations for uncompromised performance. 2D-, Stereo- and Tomo-PIV measurements are realized using torpedo designs or compact vertical borescope setups.



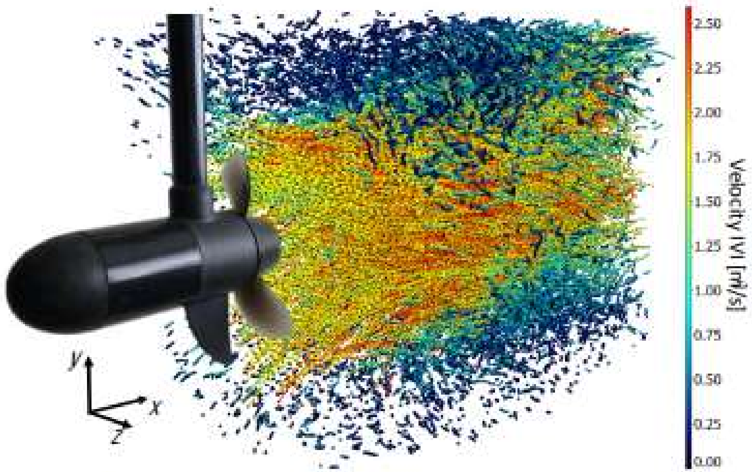


Figure 7: STB particle tracks in the propeller wake in 15 consecutive time steps color coded by velocity magnitude.

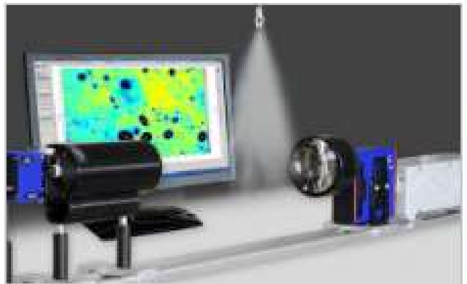
Other Product range

FlowMaster
Advanced Flow Field Imaging
PIV, PTV, LDV

FluidMaster
Scalar Flow Imaging
LIF, Rayleigh, BOS

FlameMaster
Species, Temperature, Soot
(Laser) Imaging in Flames

EngineMaster, ICOS
Engine Diagnostics
Optical Engine Indication



ParticleMaster
Size, Shape, Velocity
Shadowgraphy, IMI

SprayMaster
Spray Analysis, Quality Control
(Laser) Imaging in Sprays

StrainMaster
Surface (Volume) Deformation, Strain
DIC, DVC

Cameras
Intensified, High-Speed
CCD, CMOS

- Visit us www.lavision.de for more details

Thank you for your attention!

ARUN RAJ

arun@lavision.com

VIVEK

vivek@tesscorn-aerofluid.com