Particle Image Velocimetry for Fluid Dynamics Measurements

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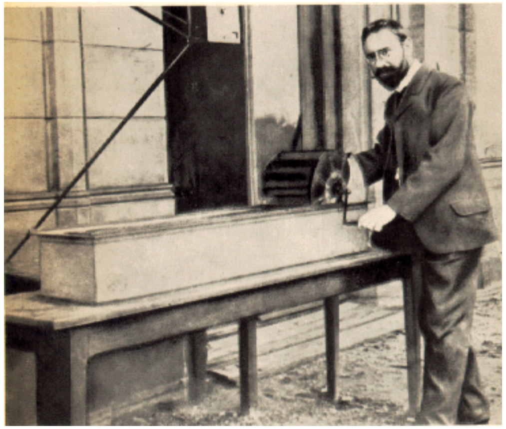
Presentation

- A bit of history
- What is PIV?
- How to perform PIV measurements?
- Which PIV system and for What?
- How to post-process the Data?

A Little Bit fo History

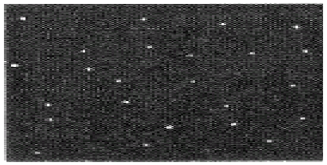
- Origines: Flow visualizations
- 70's: Laser Speckle Velocimetry
- 80's: LSV,PTV, PIV,
- LASER development
- CCD cameras development
- Computers development
- First scientific paper on PIV (Adrian 1984 in Appl Opt)
- First commercial PIV systems 1988 (TSI Inc.)



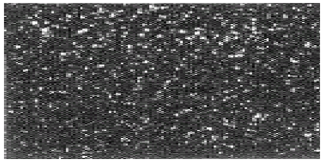
Ludwig Prandtl operating his water channel in 1904

What is PIV?

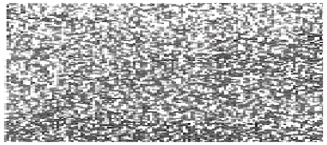
Flow visualization



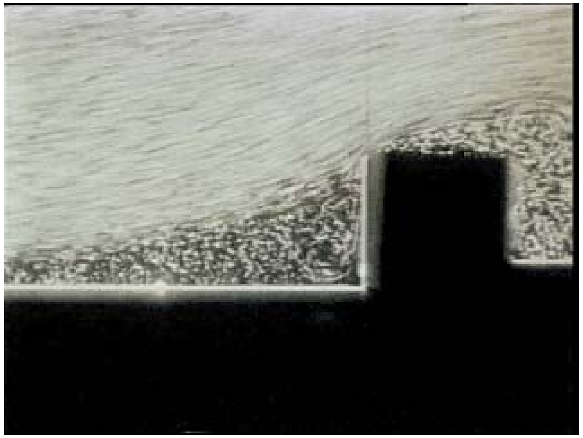
Particle tracking velocimetry (PTV)



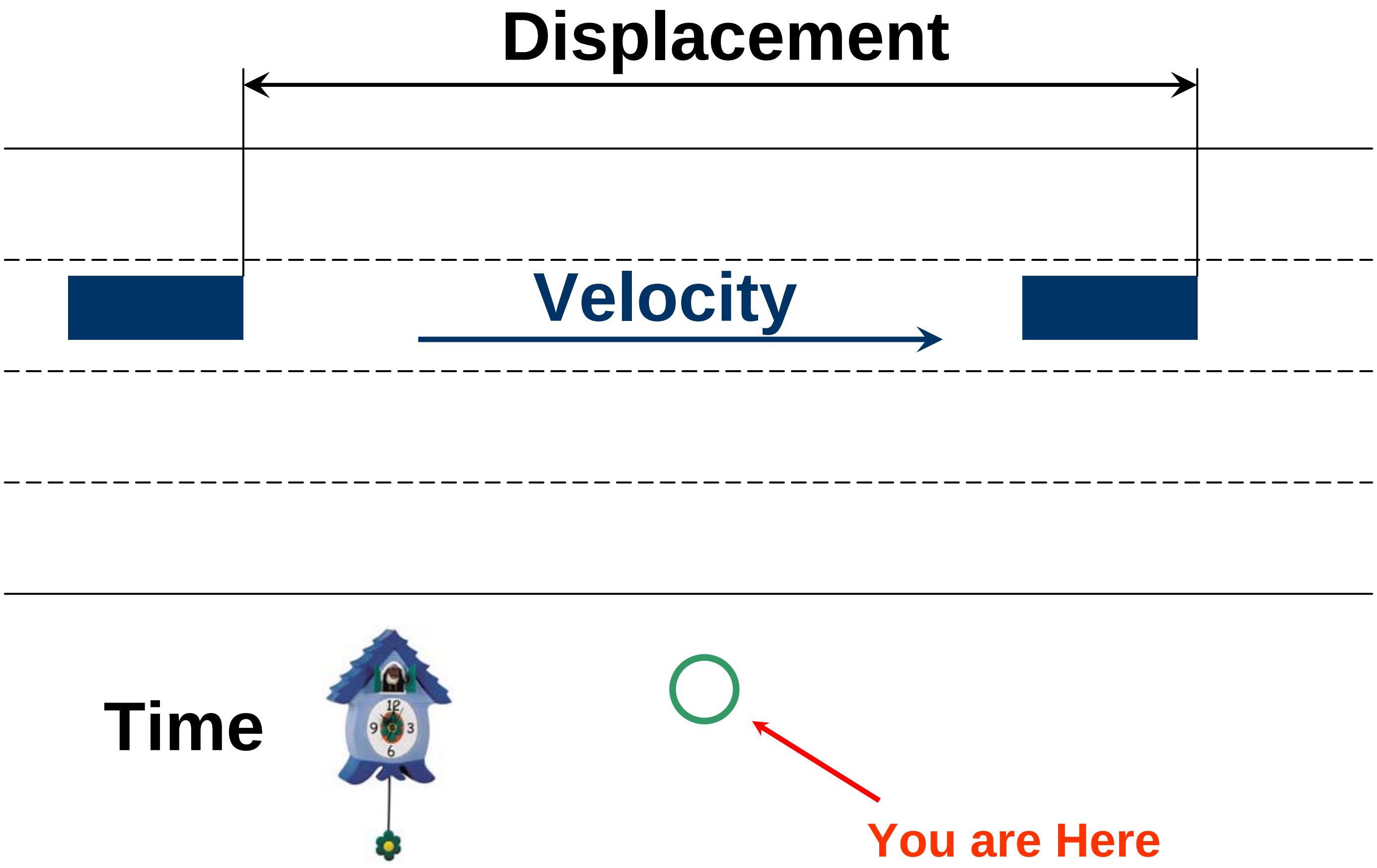
Particle image velocimetry (PIV)



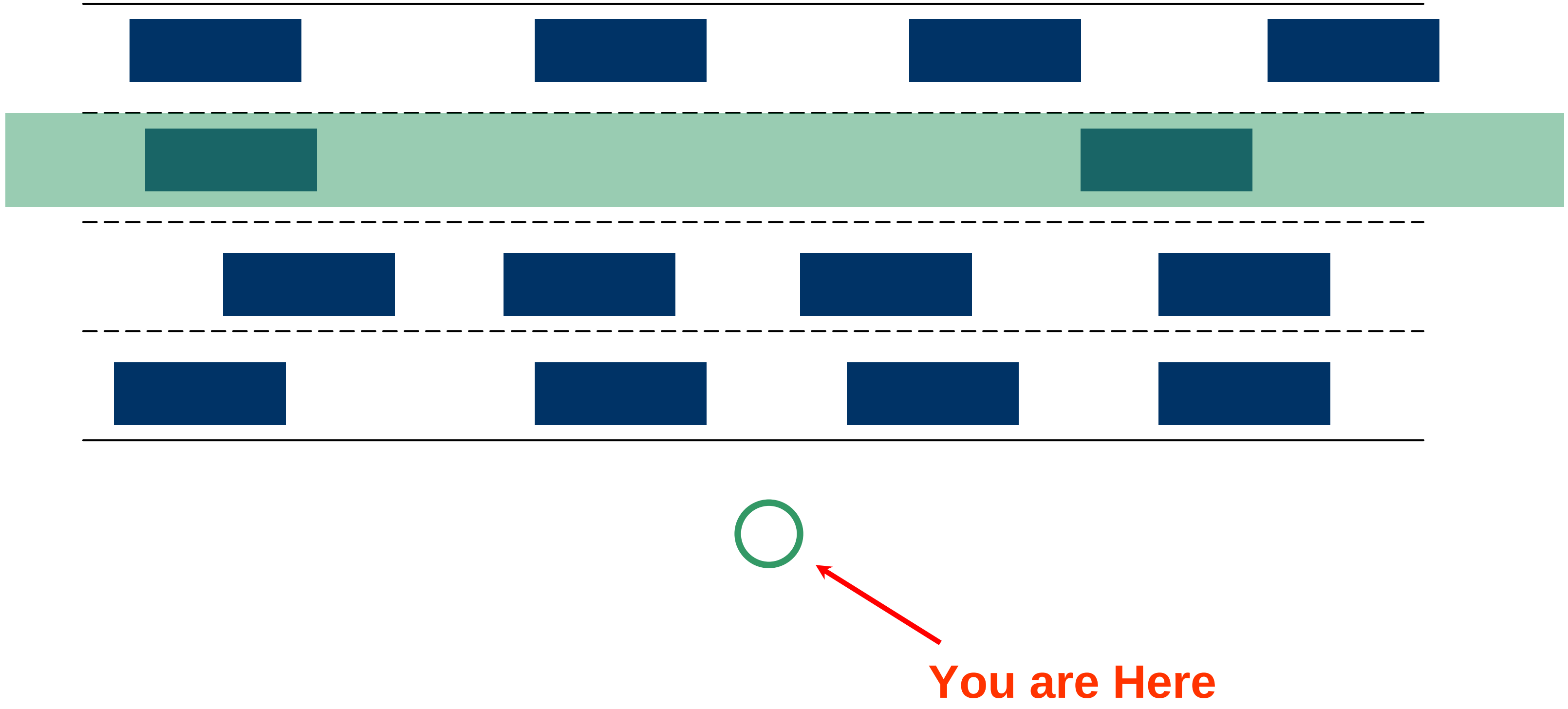
Particle soeckle velocimetry (PIV)



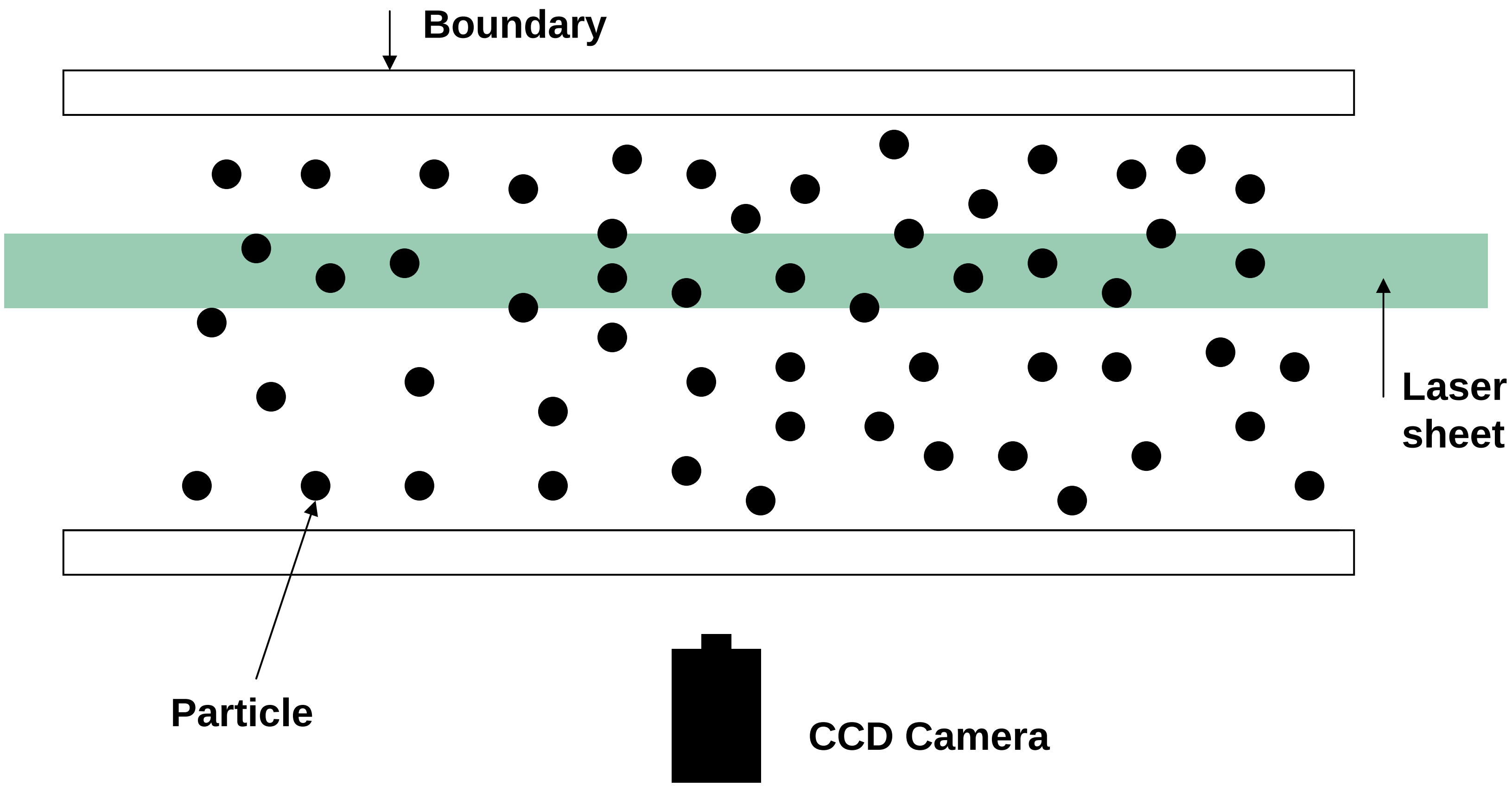
Very Basic Idea Behind Optical flow measurements

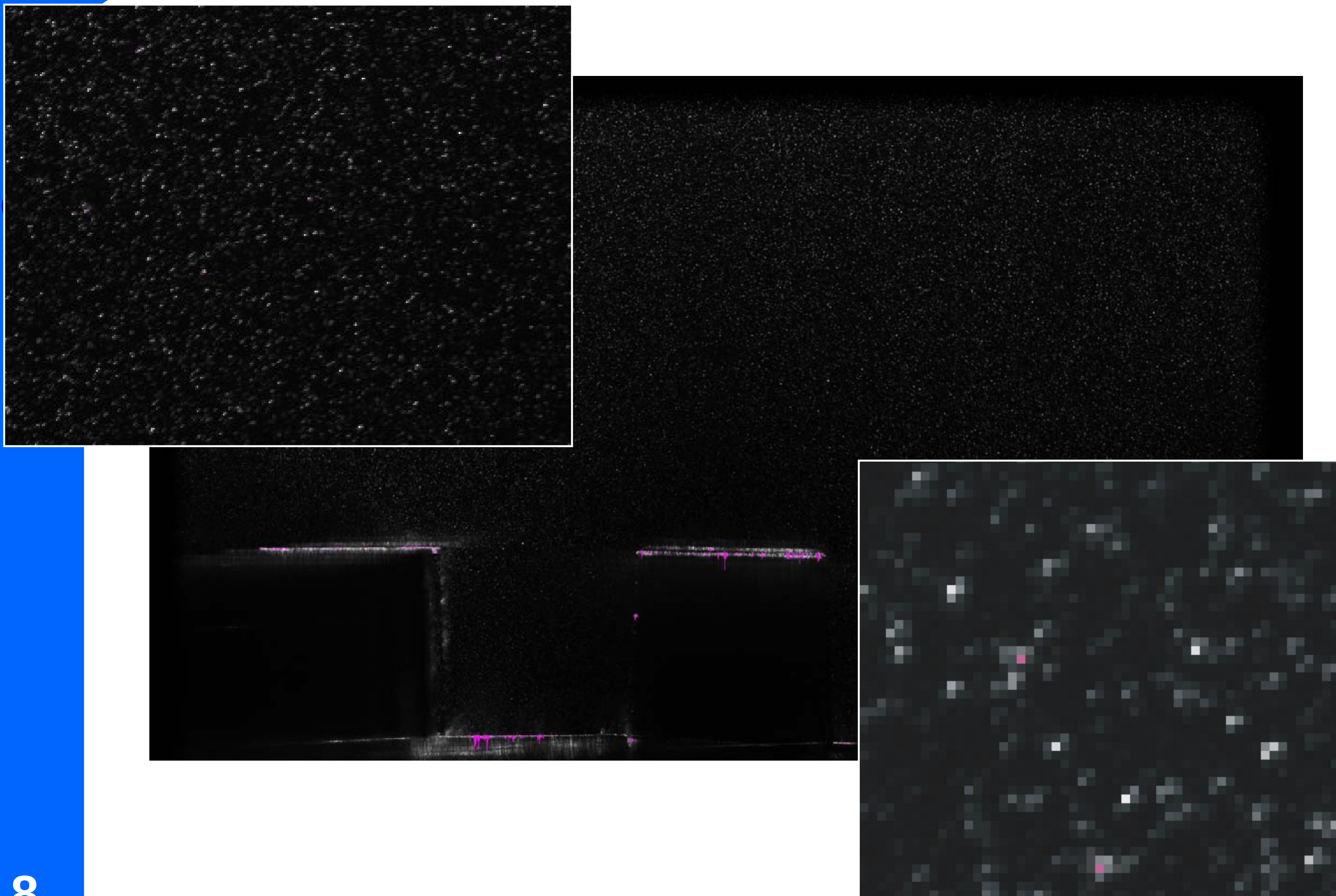


Very Basic Idea Behind Optical flow measurements

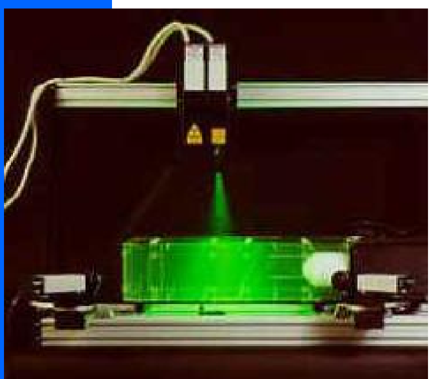


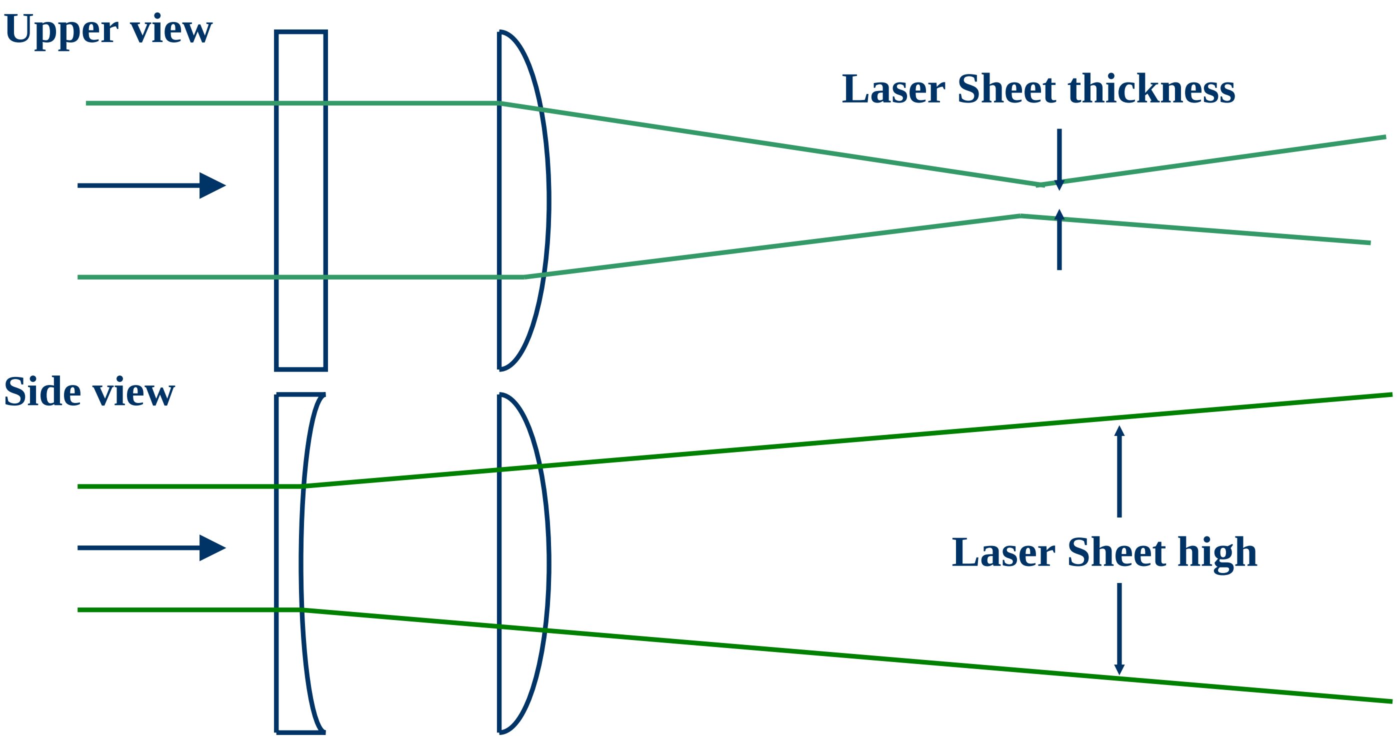
Very Basic Idea Behind Optical flow measurements





Laser Sheet





Thin laser sheet
Thick laser sheet

out of plane movement
decrease in S/N

Laser Sheet

- A large amount of light (from 20 mJ to 400 mJ) must be available in a short time (~ 5ns).

- Inter-pulse (Δt) timing may vary from less than 1μs to many ms depending upon the velocity of the flow.

- The repetition rate of a pulsed laser is typically 10-30Hz

$\longrightarrow$ adequate only for velocities < 1 m/s

Laser Sheet

Which Laser and for what?

- Double pulsed laser (Δt: 1-150 μs), 10 Hz, adequate for high-speed airflow applications.

- Dual head system (Δt: 100 ns-1s), over 50 Hz, adequate for time resolved PIV.

- Two color Laser for two-color PIV, adequate for two phase flow measurement.

Laser Sheet: Safety

The laser used are usually in Class 4

High power devices; hazardous to the eyes (especially from reflected beam) and skin; can be also a fire hazard

- **Keep all reflective materials away from the beam.**
- **Do not place your hand or any other body part into the laser beam.**
- **Wear a safety glasses (same wavelength as the laser beam).**
- **Work back to the laser sheet.**
- **Put a light to indicate that the laser is on.**

The main Point: The particles

Which particle size to choose?: the size dilemma !!!

Light diffusion by a particle: Mie's Theory

Applied for $d_p >> \lambda_{light}$

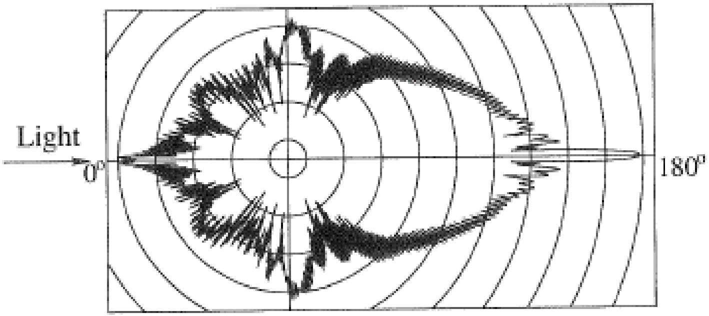
A part of the light is scattered at 90°:

$$\frac{side\ intesity(90^o)}{forward\ intesity} = 10^{-3}$$

$$\frac{CCD\ captured\ light\ intensity}{Laser\ light\ intensity} = 10^{-5}$$

Light diffusion ~ $1/r^2$: minimize the distance camera-laser sheet

A <u>large</u> particle scatters more light than a small particle.



Light scattering by a 10μm glass particle in water (from Raffel 1998)

The main Point: The particles

Which particle size to choose?: the size dilemma !!!

For spherical particles, in a viscous flow at low Reynolds number (Stokes flow)

Velocity shift due to difference in density

$$U = d_p^2 \frac{(\rho_p - \rho)}{18 \, \mu} \, a$$

For gravitational velocity : a ≡ g

The main Point: The particles

Which particle size to choose?: the size dilemma !!!

Step response of a particle

$$\tau_s = d_p^2 \frac{\rho_p}{18\ \mu}$$

Measures the tendency of a particle to attain velocity equilibrium with fluid

A <u>small</u> particle follows better the flow than a large particle.

The main Point: The particles

Which particle size to choose?: the size dilemma !!!

	Follow the flow	Light scattering	Step response
Small particles	Good	Bad	Good
Large particles	Bad	good	Bad

The main Point: The particles

Which particle size to choose?: the size dilemma !!!

For liquids

- Polystyrene (10-100 μm); aluminum (2-7 μm); glass spheres (10-100 μm).

Usually particle diameter of 10-20 μm is a good compromise.

The main Point: The particles

Which particle size to choose?: the size dilemma !!!

For gas

- Polystyrene (0.5-10 μm); aluminum (2-7 μm); magnesium (2-5 μm); different oils (0.5-10 μm).

- Due to the great difference between the index of refraction of gas and particles: small particles in gas scatter enough light to be detected

Usually particle diameter of 1-5 μm is a good compromise.

The main Point: The particles

Which particles concentration?

- The probability of finding a particle within the region of interest: 1>> Prob >0.

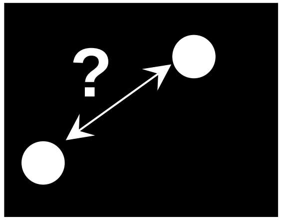
Usually a concentration of 15-20 particles/mm^3

Higher particle concentrations are either not achievable or not desirable fluid dynamically (to avoid a two phase flow effect)

CCD Camera

Particle image acquisition

Single frame/ multi-exposure



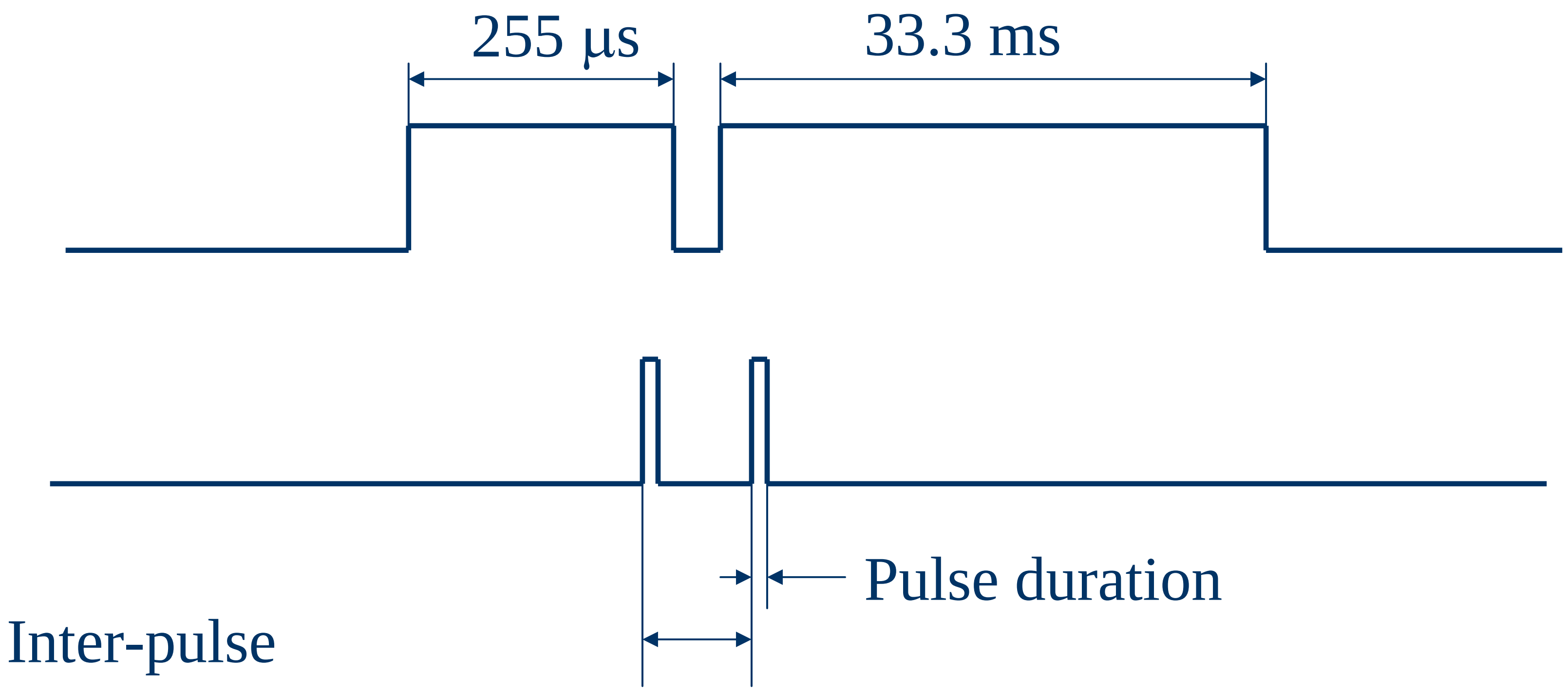
Multi-frame/ multi-exposure

Ambiguity in the direction of the flow

The spatial resolution of CCD arrays is at least two order of magnitude lower than photographic film.

CCD Camera

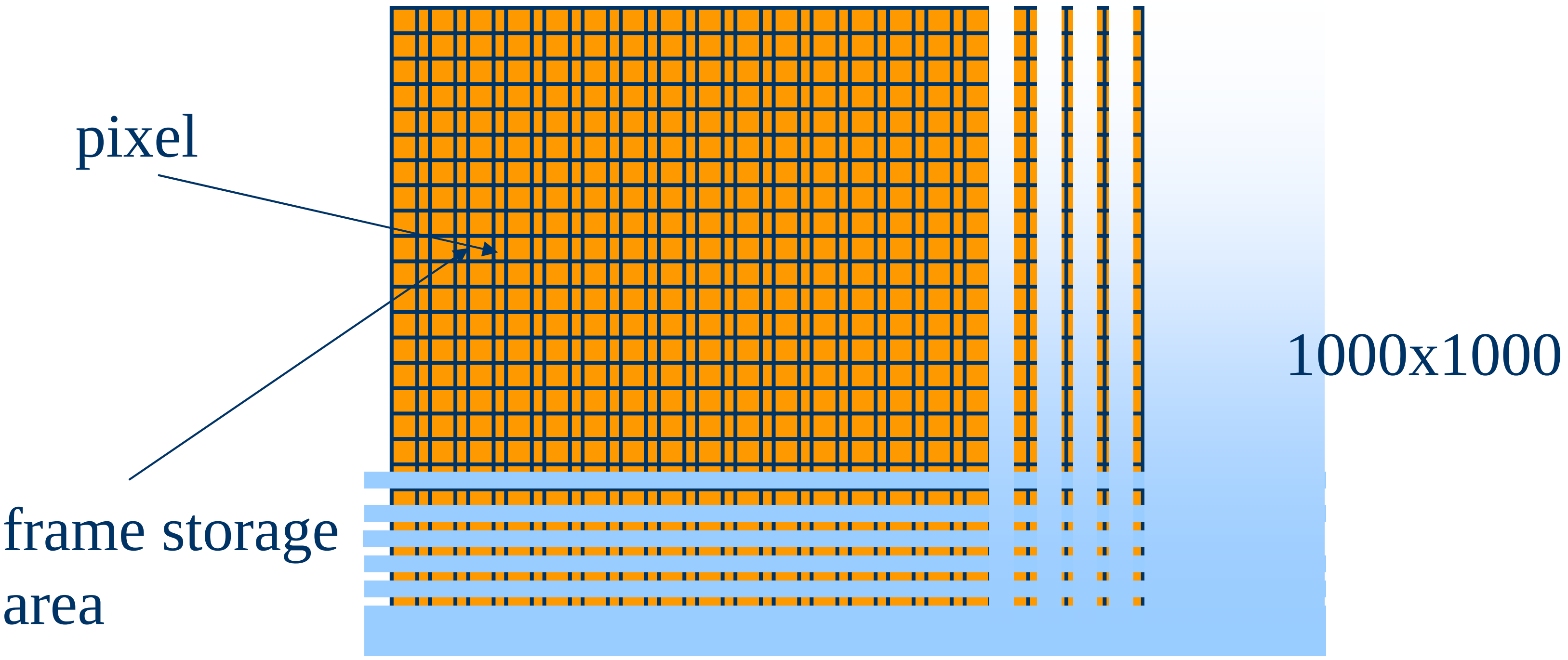
Particle image acquisition



CCD Camera: Frame-stradelling technique

Particle image acquisition

Transfert time: - pixel to frame storage area: 500 ns
- frame storage area to PC: 33 ms



CCD Camera

Particle image acquisition

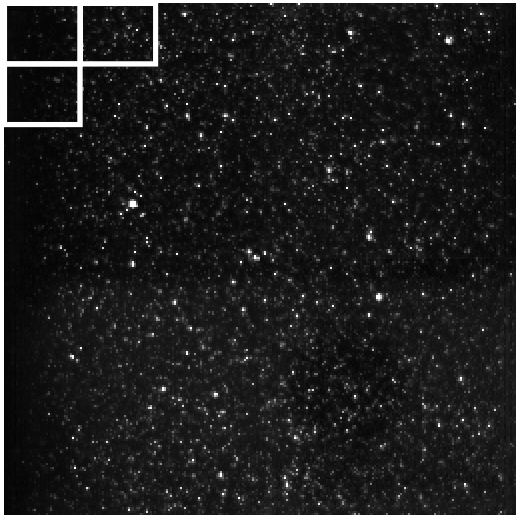
What do you want from you camera?

- **Record sequential images in separate frames.**
- **High spatial resolution.**
- **Capture multiple frames at high speed.**
- **High sensitivity.**

Velocity determination

Each image is divided into a grid of small sections known as interrogation areas (8 to 64 pixels).

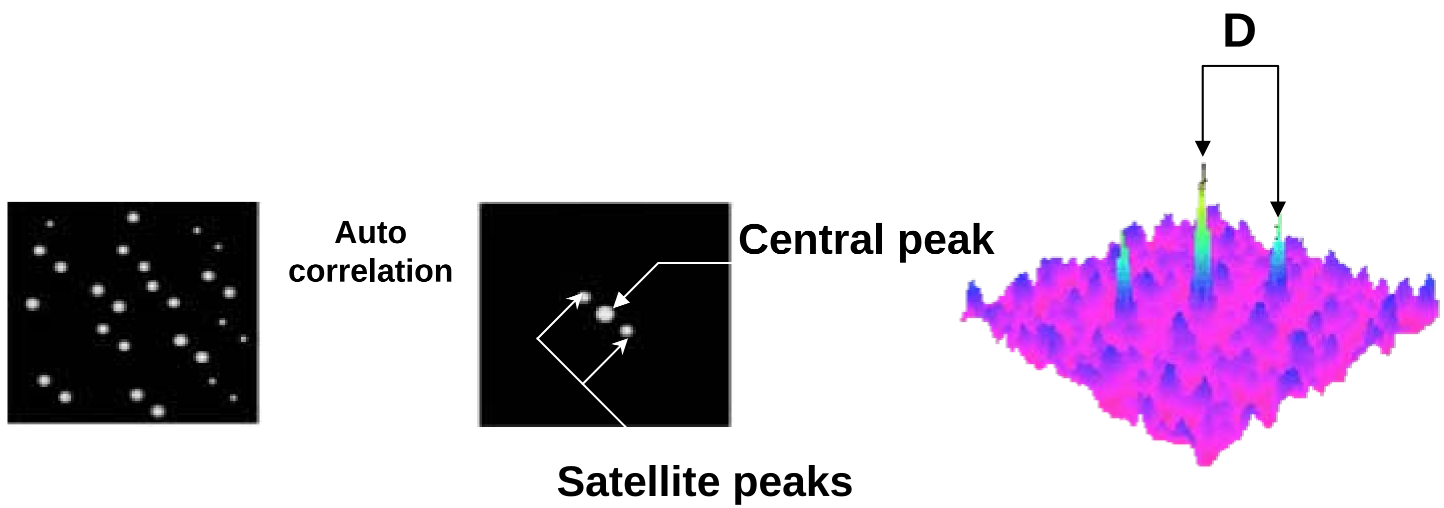
The mean displacement (D) within each interrogation area is calculated and divided by the inter-pulse (Δt)



⟶ Local mean velocity

Velocity determination

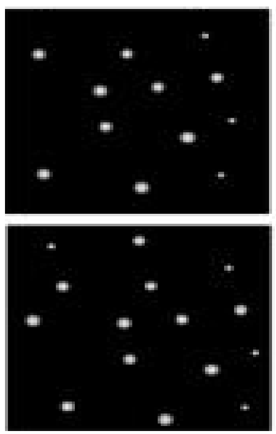
How to calculate de particles displacement: Auto-correlation



- The displacement D must be enough important to satellite peaks to be discernable from the central peak.
- Directional ambiguity.

Velocity determination

How to calculate de particles displacement: Cross-correlation

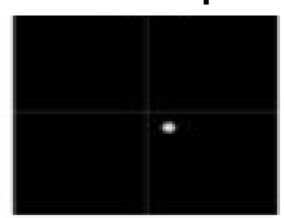


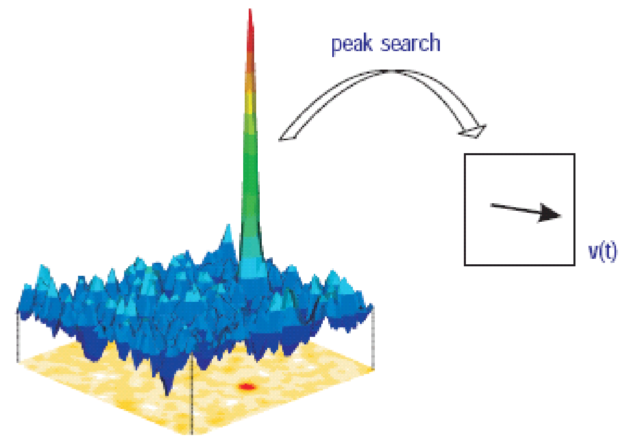
t=0

Cross correlation

t=Δt

Output correlation plan





- No directional ambiguity.
- Even very small displacements can be measured (~d_p).

Velocity determination

FFT based cross-correlation

Cross correlation fonction: 2 $\times N^2 \times N^2$ operations

Cross correlation using FFT:

$$R(i,j) = f(i,j) \otimes g(i,j) \Leftrightarrow FFT(R(i,j)) = F(u,v).G^*(u,v)$$

Number of operations: $N^2 \log_2 N$

$\Rightarrow$ **In practical applications FFT is used for cross-correlation.**

Velocity determination

FFT based cross-correlation

Limitations of FFT based cross-correlation

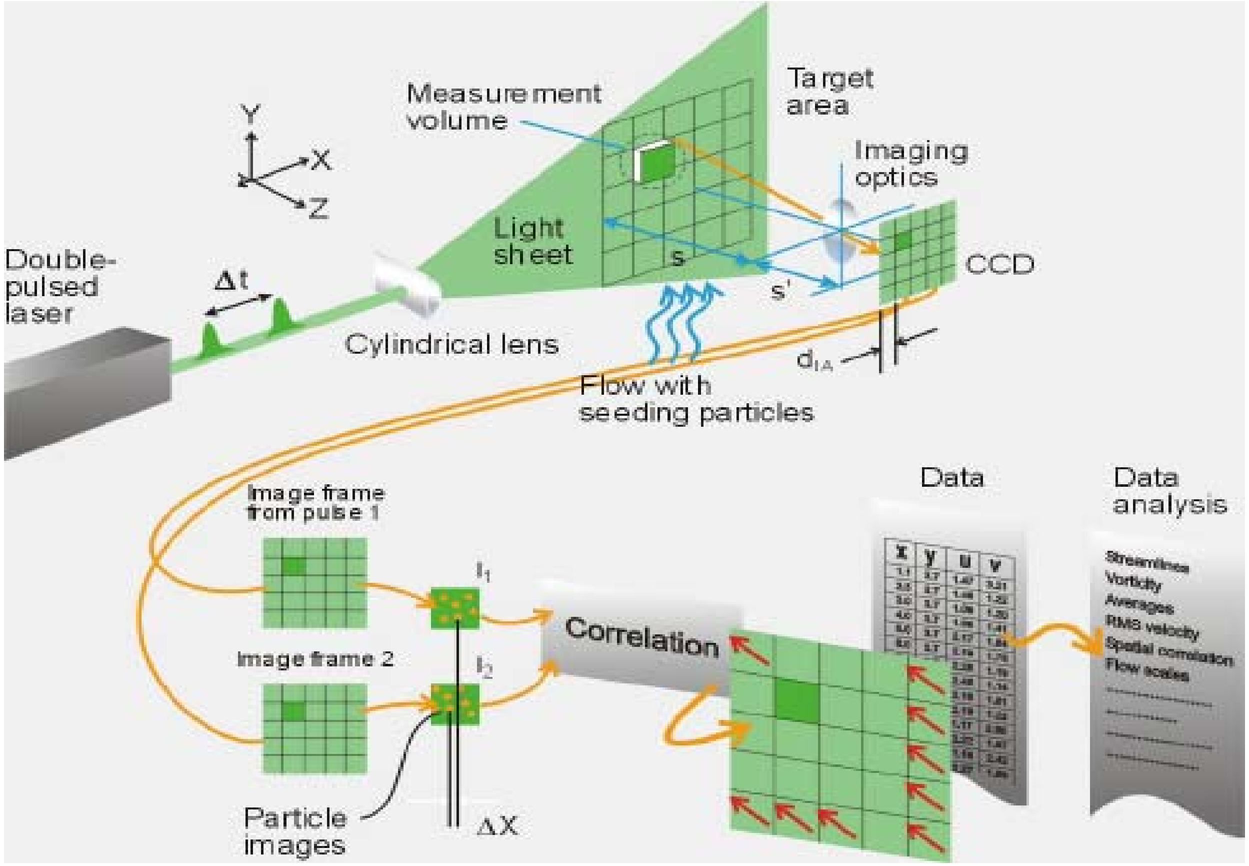
Direct cross correlation can be defined for a finite domain, whereas FFT based cross-correlation is well defined for infinite domain.

The two sub-samples have to be of square and equal size (N) and a power of 2 (8×8; 16×16; 32×32; 64×64).

$\Rightarrow$ A loss in spatial resolution when N has to be selected larger than required.

Velocity determination

Summary of PIV measurement



Velocity determination

Optimization of the cross-correlation

- The displacement of the particles during inter-pulse duration must be less that ¼ of the interrogation area size: “the ¼ law”

- To increase spatial resolution an interrogation cell overlap of 50% can be used.

- Number of particle per interrogation area: 10-15.

- Standard and deformed window shifting.

- Using PTV and PIV.

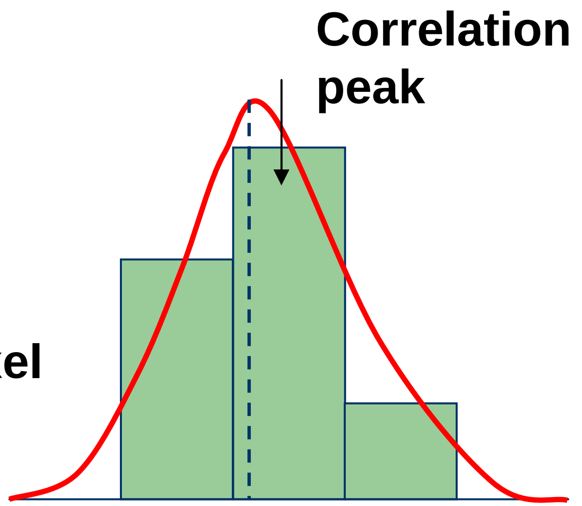
Velocity determination

Optimization of the cross-correlation

Sub-pixel interpolation

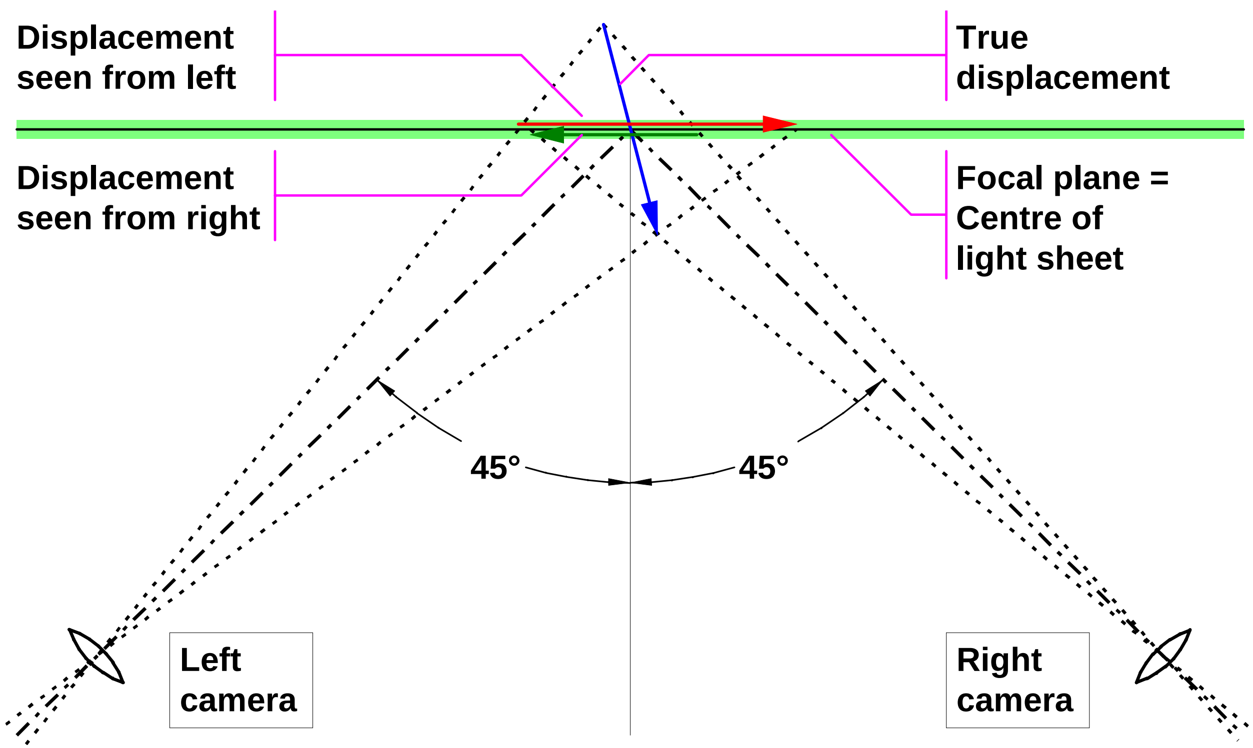
Standard cross-correlation: 1 pixel

Standard cross-correlation and sub-pixel interpolation: 0.1 pixel



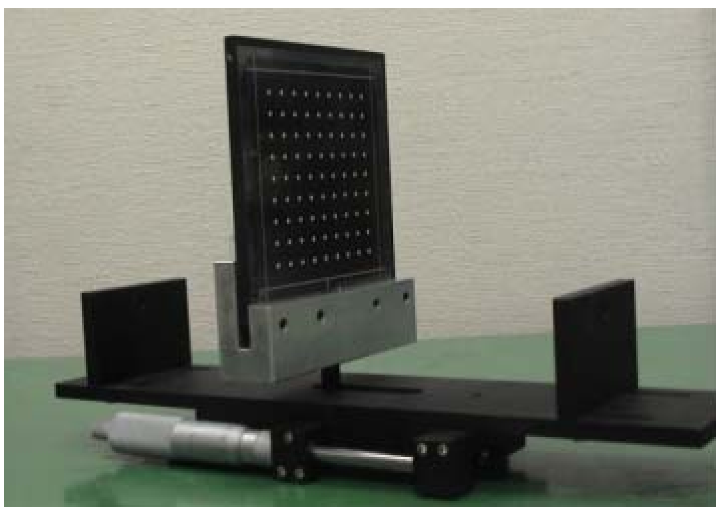
Other PIV techniques

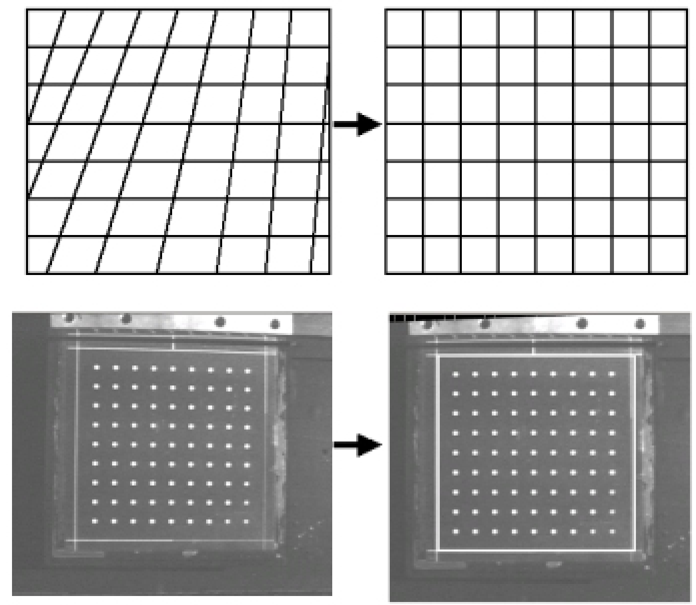
3D stereoscopic PIV



Other PIV techniques

3D stereoscopic PIV

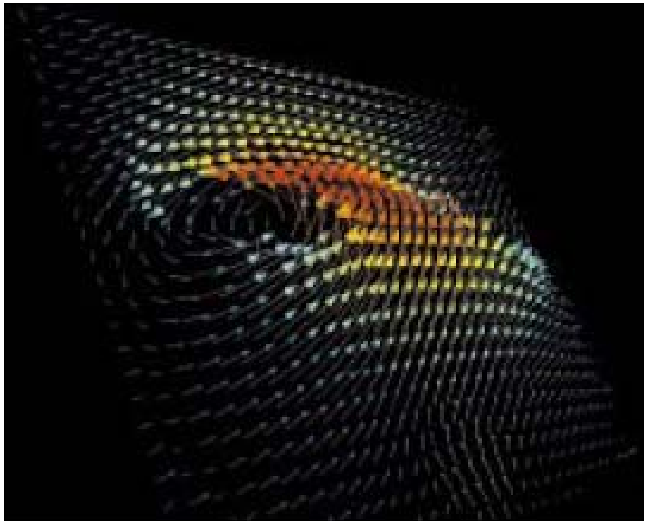




(a) Original image (b) Transformed image

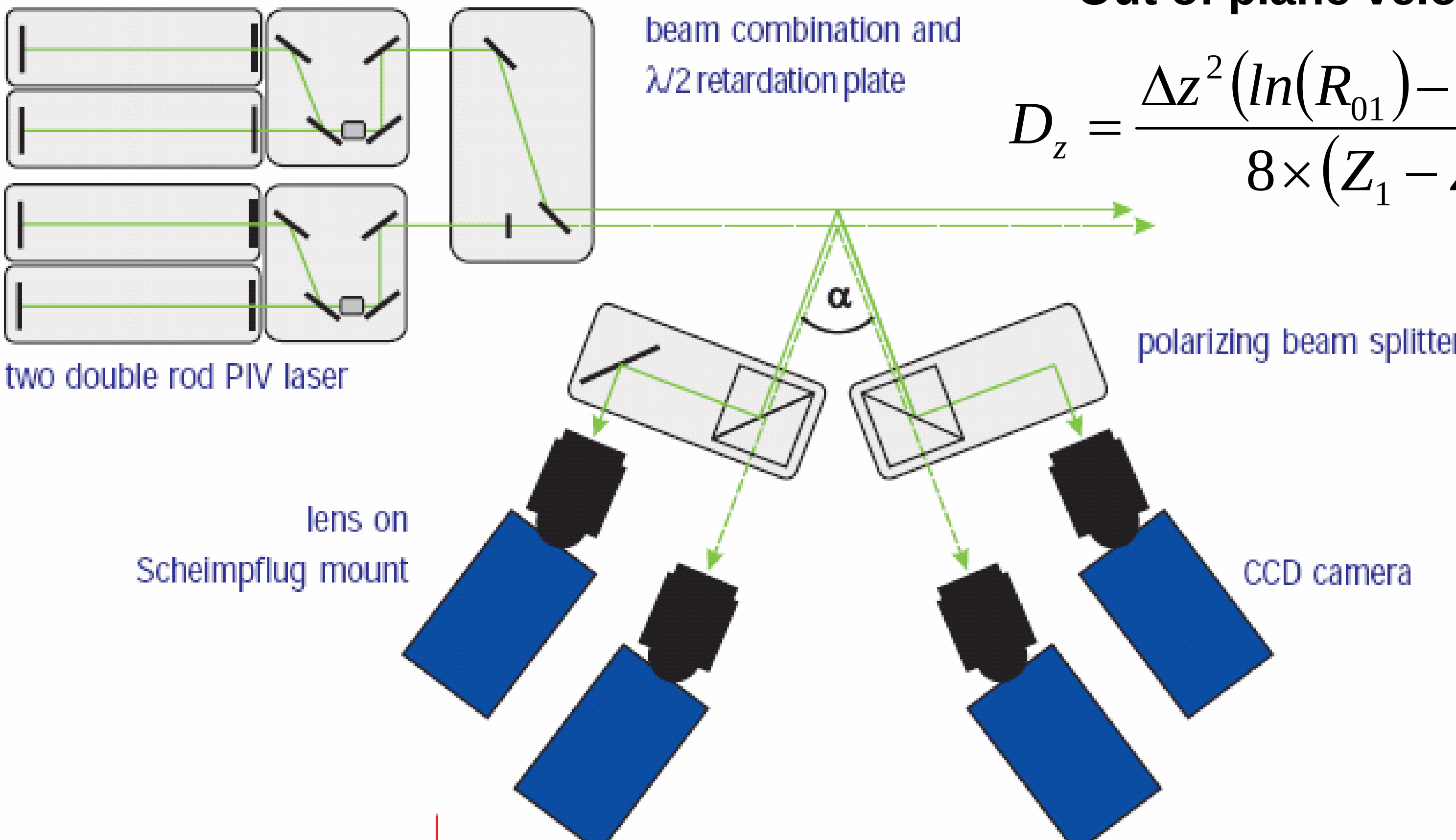
Other PIV techniques

3D stereoscopic PIV



Other PIV techniques

Dual Plan PIV

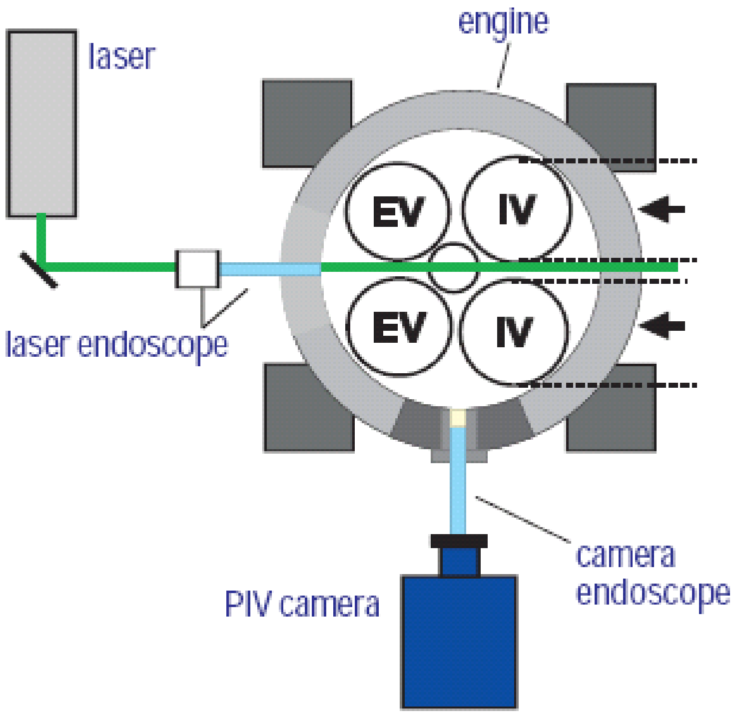


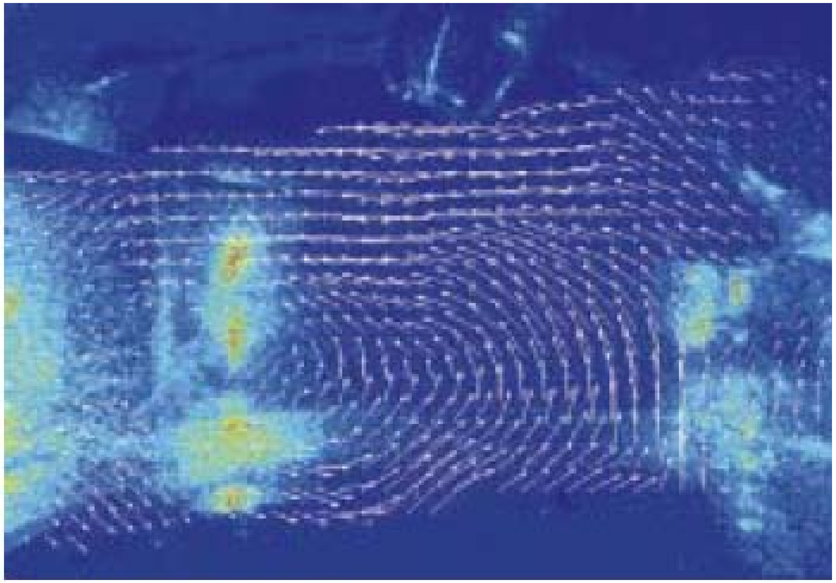
Out of plane velocity

$$D_z = \frac{\Delta z^2 \left(ln\left(R_{01}\right) - ln\left(R_{21}\right)\right)}{8 \times \left(Z_1 - Z_0\right)}$$

Other PIV techniques

Endoscopic PIV





tumble flow in IC engine

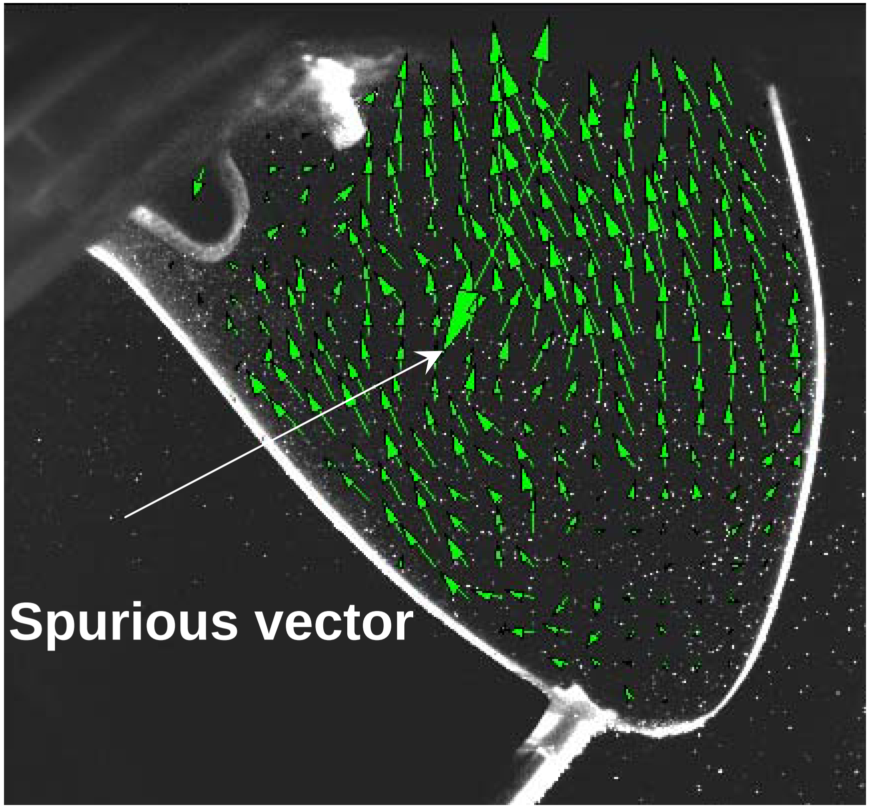
Post-processing PIV data

Spurious vectors !!!!!

- Low particles density
- inhomogeneous particles seeding
- Particles within a vortex
- low S/N
- 3D movement of the particles

Why the spurious vectors have to be eliminated ?

Induce errors in velocity derivation.



Post-processing PIV data

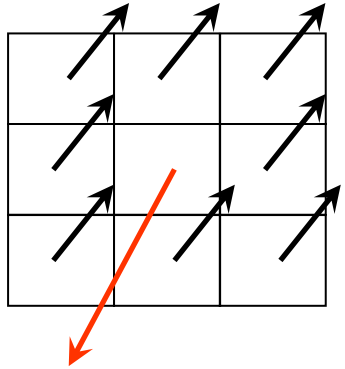
How to eliminate spurious vectors?

- Fix a velocity threshold (ex. Max velocity 10m/s)

- Mean local filter (may be biased by the surrounding spurious vectors)

- Temporal median filter

- Median local filter



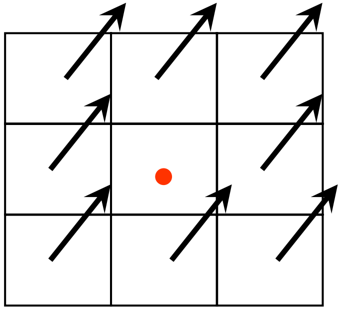
- Application of the continuity equation

- Calculation of the circulation

Post-processing PIV data

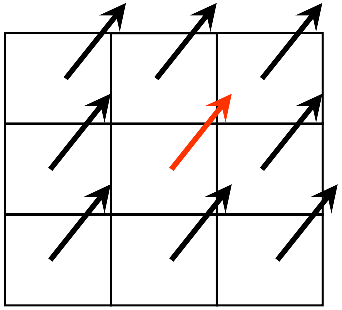
How to replace spurious vectors?

- Mean or median of the surrounding velocities.



- A weighted average of the surrounding velocities.

- An interpolation filtering (the spurious vectors are considered as high frequency signals).



Post-processing PIV data

Estimation of differential quantities

Finite difference method: forward, backward, <u>center</u>, Richardson, …

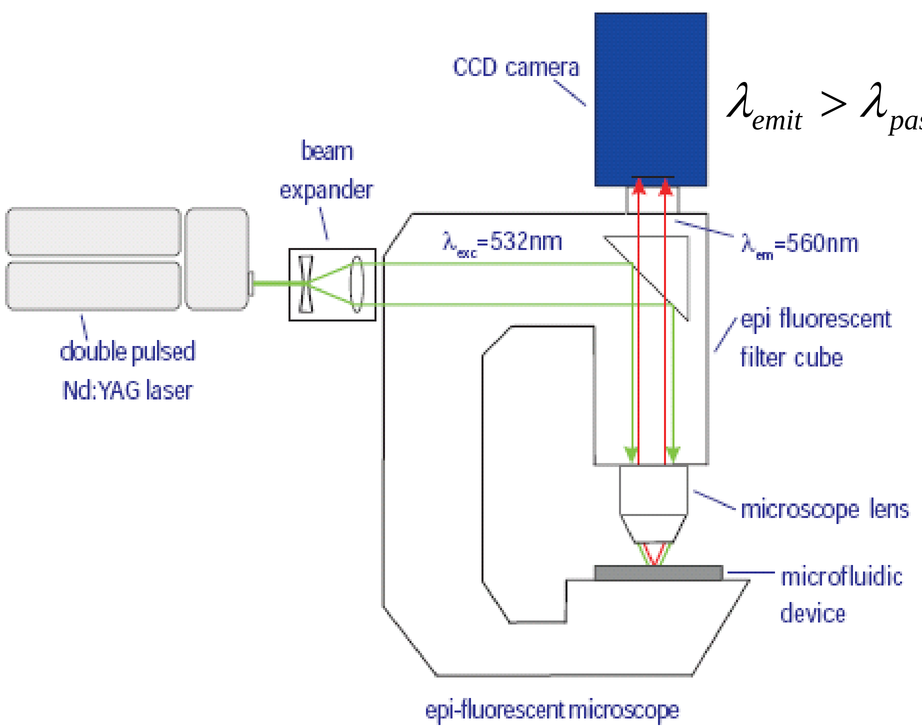
Determination of the vorticity from the circulation (the 8 points circulation method)

Turbulence micro scales (only with high speed PIV)

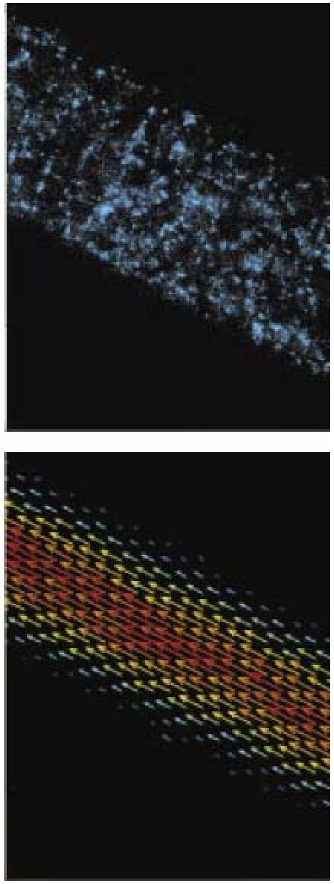
Pressure field

Other PIV techniques

Micro PIV



$$\lambda_{emit} > \lambda_{pass} > \lambda_{laser}$$



Polychromatic μPIV can be used for two phase flow.

Other PIV techniques

Micro PIV

The same old story: the particles

- Particles size: from nanometers to several microns.

- The particles should be large enough to dampen the effects of Brownian motion:

Brownian motion results from the interaction between the particles. This prevents the particles to follow the flow.
The relative error in the measured particle displacement is:

$$\varepsilon = \frac{1}{u}\sqrt{\frac{2D}{\Delta t}}$$