PARTICLE IMAGE VELOCIMETRY

AMME – 5292
ADVANCED FLUID DYNAMICS

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- A bit of history.
- What is PIV ?
- How to perform PIV measurements ?
- Process PIV data ?
- Further development of PIV.

A bit of history

Why use imaging?

Conventional methods (HWA, LDV)

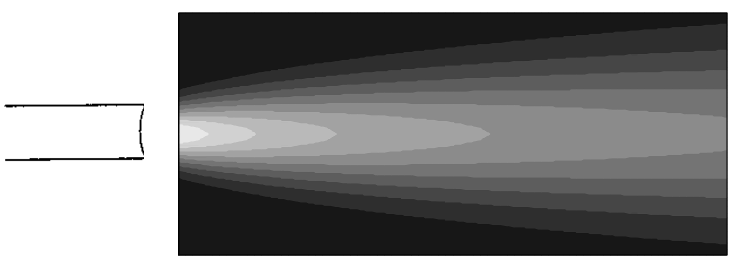
-Traversing of flow domain

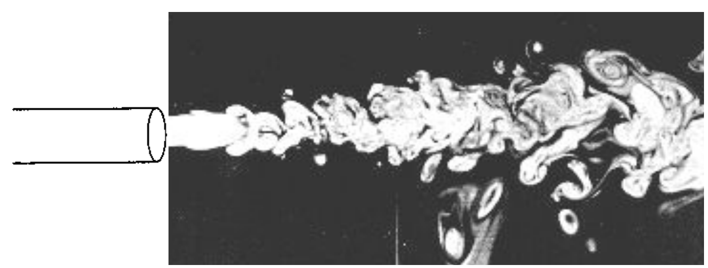
-Time consuming

-Single-point measurement

Particle imaging approaches

- Whole-field method
- Non-intrusive (seeding)
- Instantaneous flow field





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Relevant References:

An Introduction to the Theory of Fluid Flows Chapter 21 (by Durst)

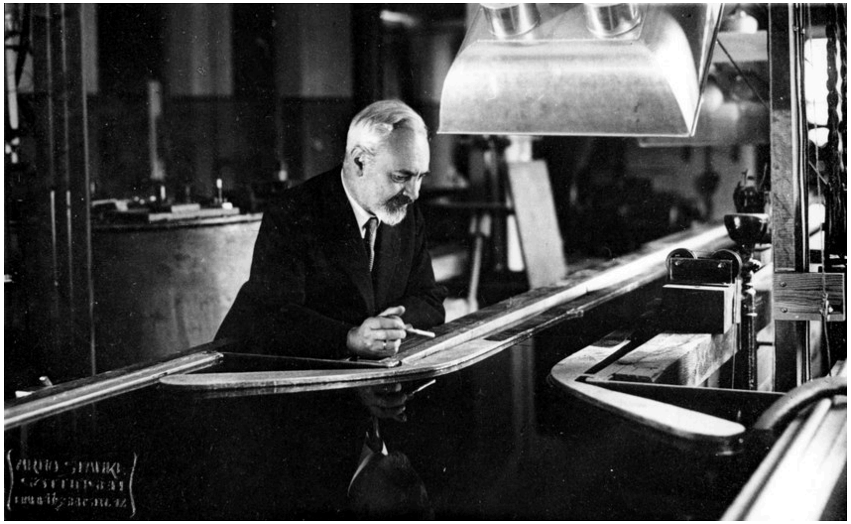
Particle Imaging Velocimetry A Practical Guide (some of Chapters 1-5) Raffel et al.

Some lecture notes of A. Kourmatzis

Information from Davis

A bit of history

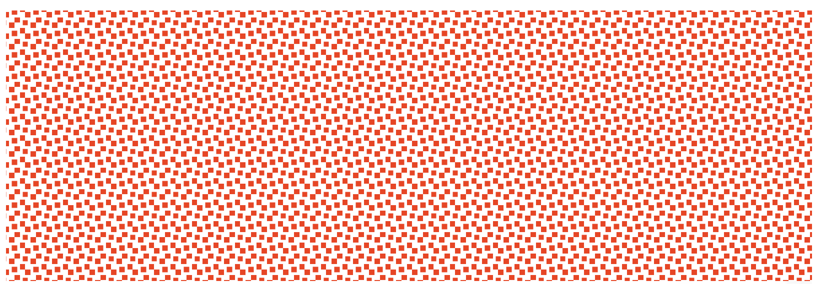
- Origins: Flow visualizations
- 70's: Laser Speckle Velocimetry
- 80's: LSV,PTV, PIV,
- LASER development
- CCD cameras development
- Computers development
- First scientific paper on PIV (Adrian 1984 in Appl. Opt.)
- First commercial PIV systems 1988 (TSI Inc.)



Ludwig Prandtl at his water tunnel

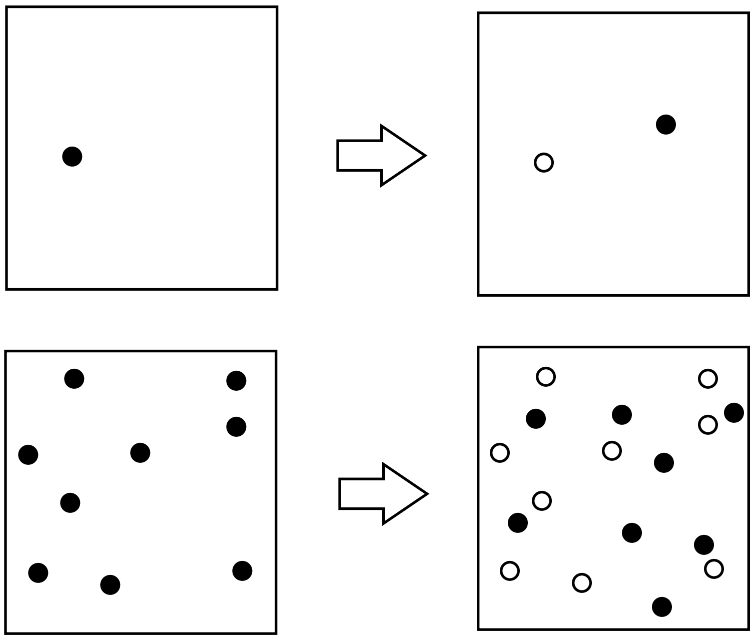
A bit of history

Particle imaging



A bit of history

Prob(detect) ~ image density (N_I)



Low image density

$N_I << 1$

Particle Tracking Velocimetry

High image density

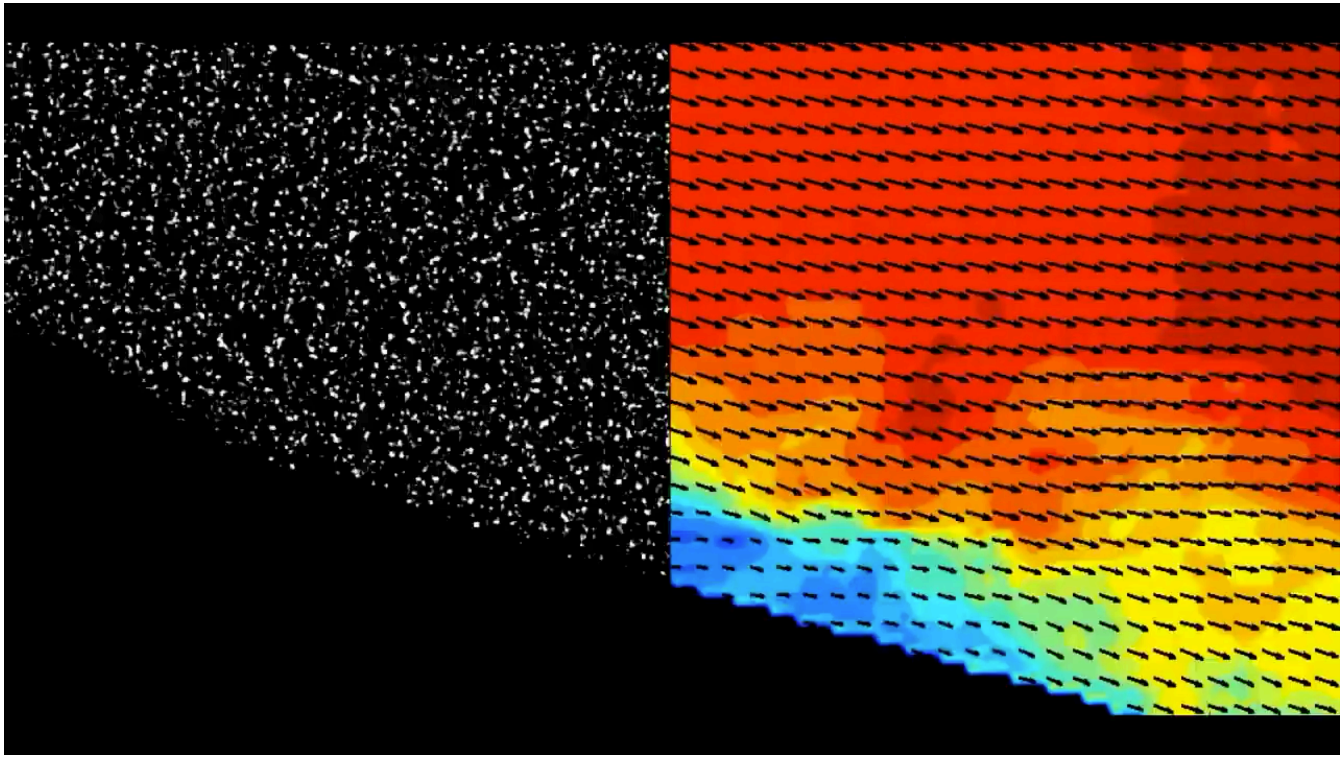
$N_I >> 1$

Particle Image Velocimetry

What is PIV ?

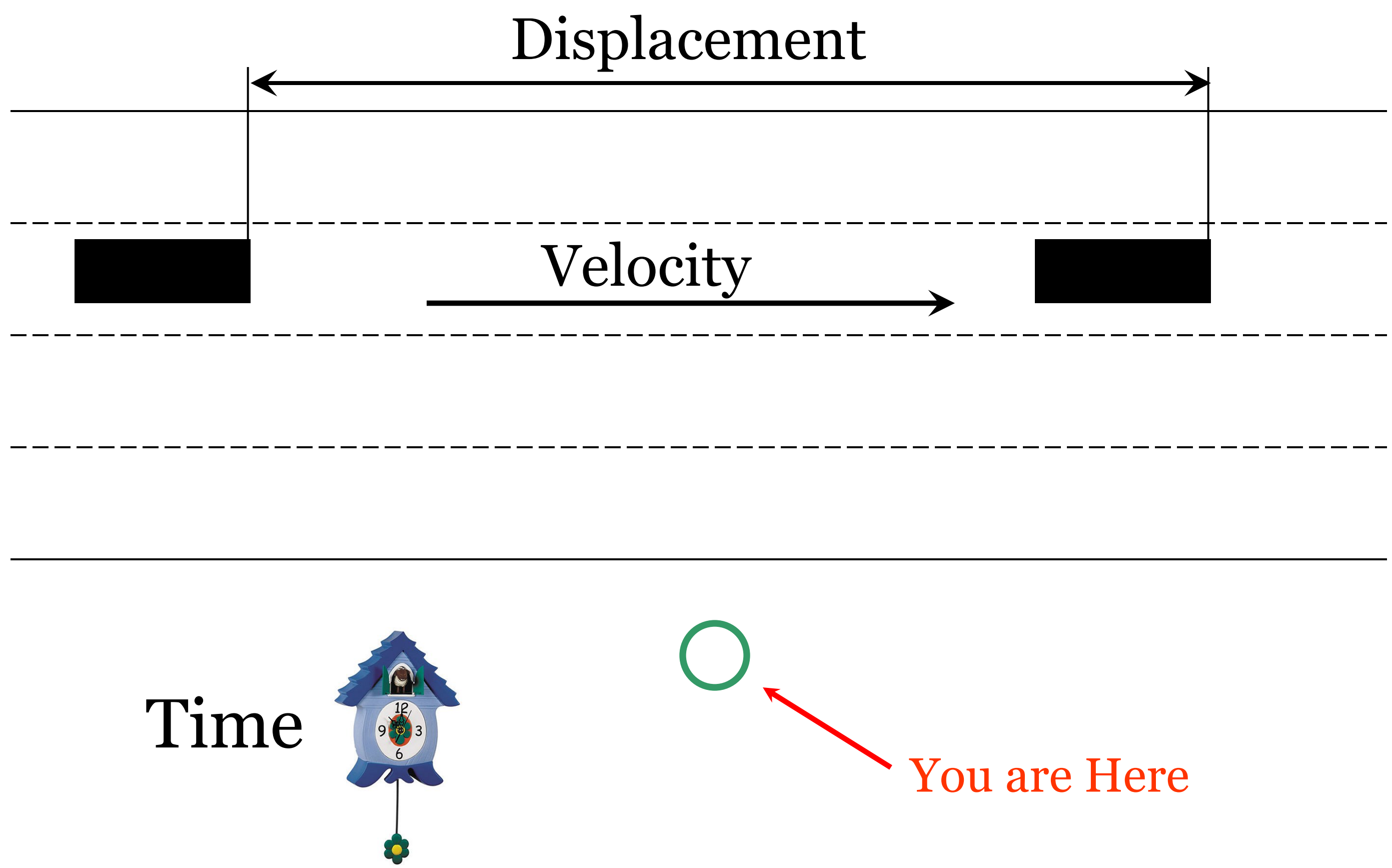
First impression of PIV measurements.

What is PIV ?



A PIV measurement of a boundary layer flow

Concept of velocity calculation

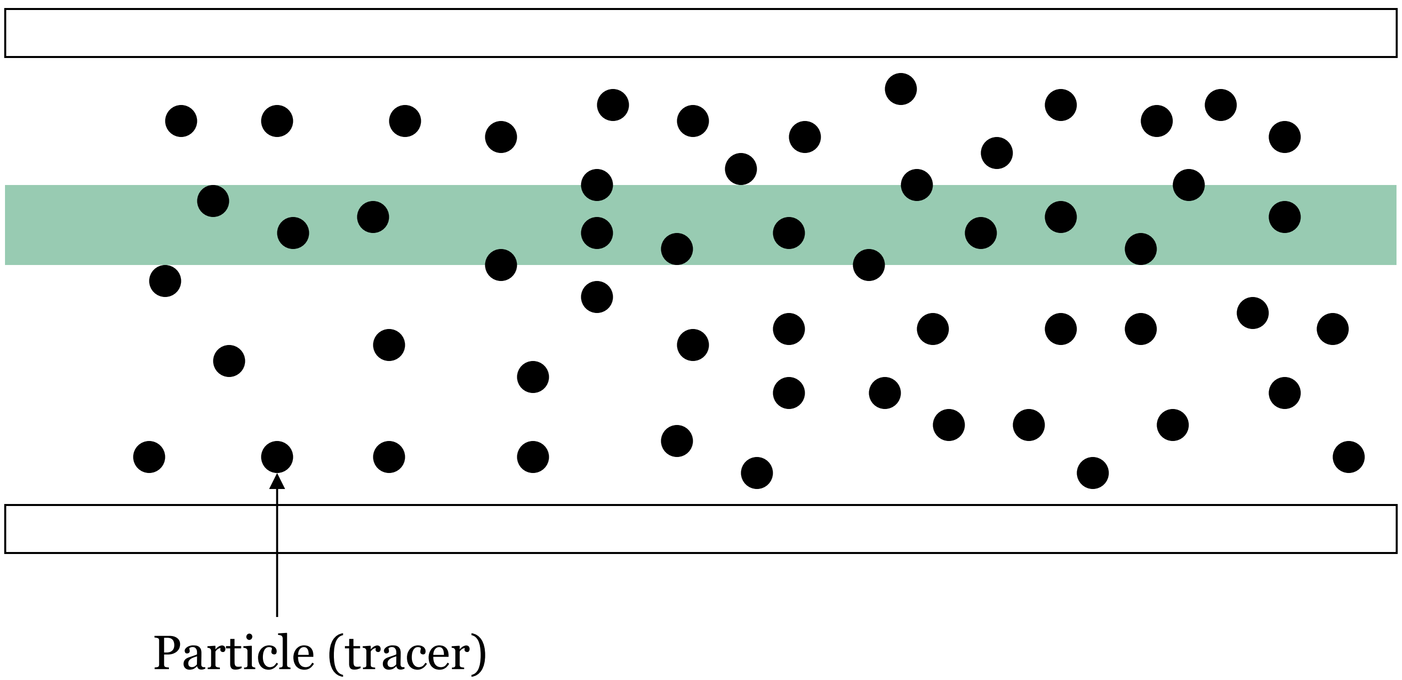


What is PIV ?

Concept of velocity calculation

What is PIV ?

Concept of velocity calculation



Perform a PIV ?

Seeding: In most applications tracer particles have to be added to the flow.

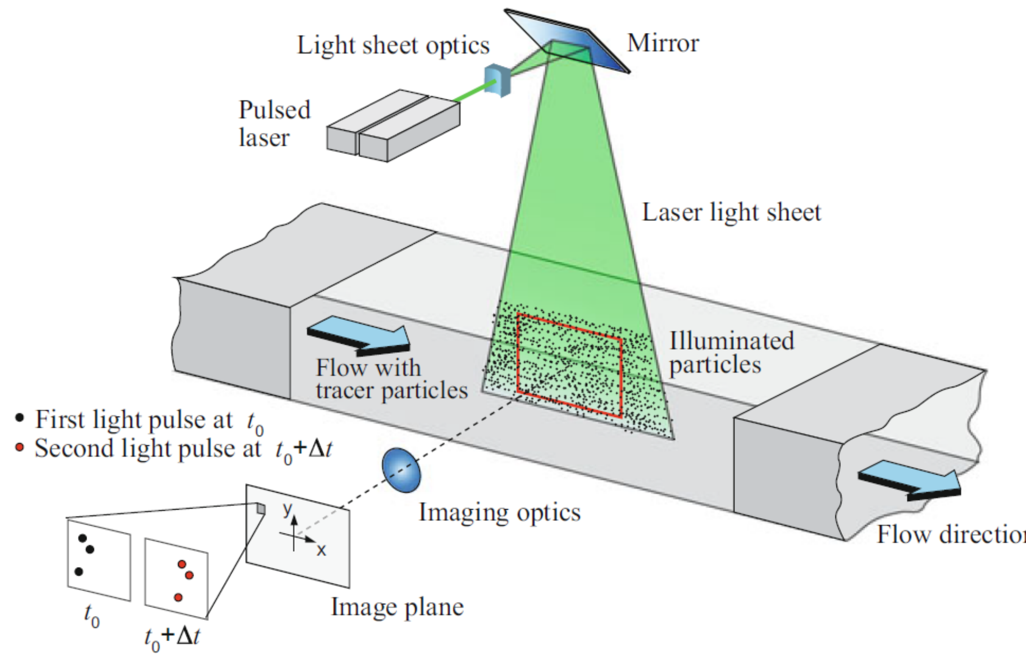
Illumination: These tracer particles have to be illuminated in a plane or a volume of the flow at least twice within a short and known time interval.

Recording: The light scattered by the tracer particles has to be recorded either on two separate frames or on a sequence of frames of a camera

Calibration: In order to determine the relation between the particle image displacement in the image plane and the tracer particle displacement in the flow, a calibration is required.

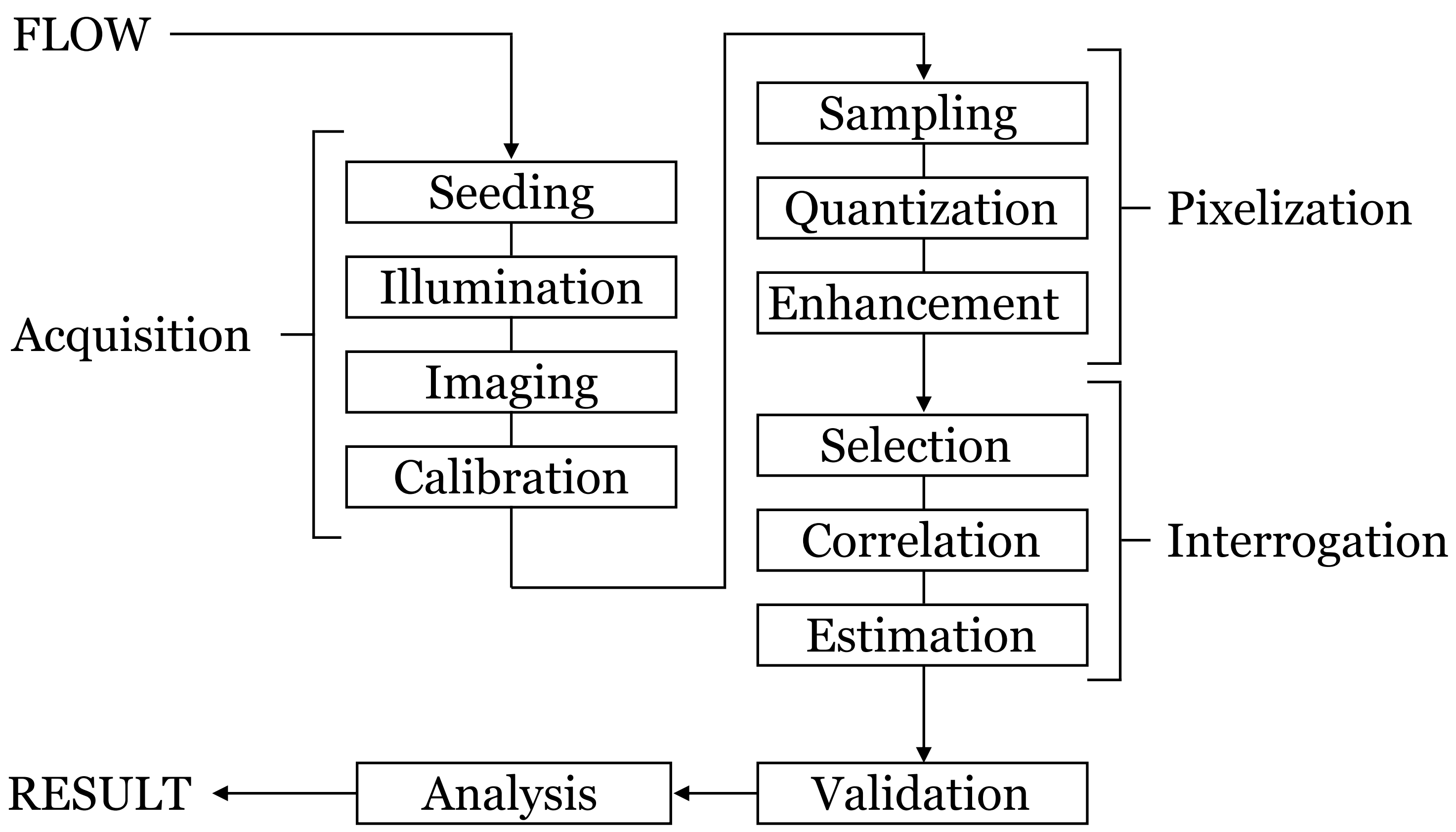
Evaluation: The displacement of the particle images between the light pulses has to be determined through evaluation of the PIV recordings.

Post-Processing: In order to detect and remove invalid measurements and to extract complex flow quantities of interest, sophisticated post-processing is required.



Experimental arrangement for planar 2C-2D PIV in a wind tunnel

Perform a PIV ?



Perform a PIV ?

Seeding
↓
Illumina.
↓
Imaging
↓
Calibrat.
↓
Sampling
↓
Enhancem.
↓
Selection
↓
Correlation
↓
Estimation

Perform a PIV ?

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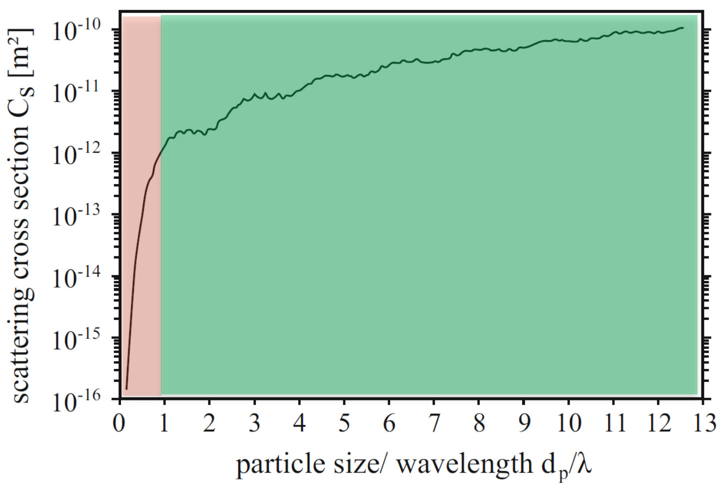
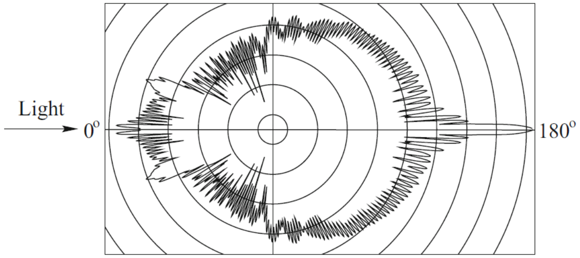
What particle size to choose?

- Scattering by tracer particles ~ **size, shape**, **refractive index**, **orientation &** **polarisation**
- Scattering capability $C_s = {}^{P_s}/_{I_0}$, where C_s is the cross section, P_s the total scattered power, and I_0 the laser intensity of the incident light.
- Particles with $d_p/\lambda < 1$ scatter in the Rayleigh regime, and particles with $d_p/\lambda > 1$ scatter in the Mie regime

A **large** particle scatters more light than a small one.





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

Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Perform a PIV ?

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

Velocity shift due to difference in density

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

(gravitational velocity : a ≡ g)

Step response of a particle

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

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

A small particle follows better the flow than a large particle.

Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Perform a PIV ?

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

Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Perform a PIV ?

Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

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.

Perform a PIV ?

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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.

Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Perform a PIV ?

Seeding density

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

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

> Usually a concentration of **5-10** particles / interrogation window

Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Perform a PIV ?

Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Seeding in air **HFSB soap fluid**

- Wind tunnels and/or large scale PIV measurements
- A proper seeding device is needed.

Seeding in flames / combustion **Aerosil**

- Less velocity leak even in strongly accelerated flows
- It can be used in hot gaseous environments with a temperature of up to 1800° C.

Seeding in liquids **Glass hollow spheres**

- The particle size of several microns leads to a strong scatter of the laser light
- Very good stability against e.g. water, fuel, oil

Perform a PIV ?

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↓
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↓
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↓
Estimation

Perform a PIV ?

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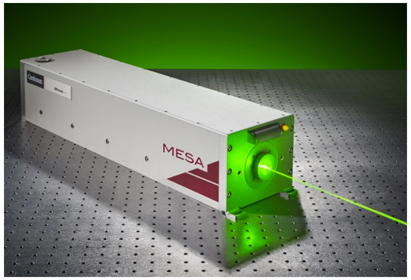
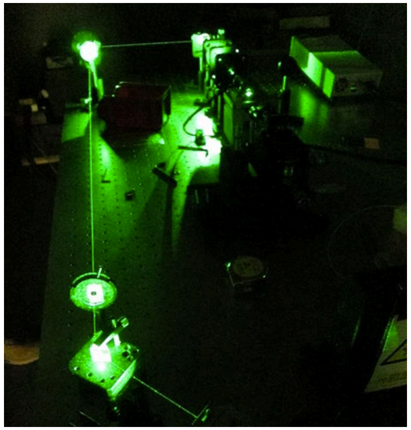
- The illumination system of PIV is always composed of **light source** and **optics**.

- Light source: such as Argon-ion laser and Nd:YAG Laser, are widely used as light source in PIV systems due to their ability to emit monochromatic light with high energy density which can easily be bundled into thin light sheet for illuminating and recording the tracer particles without chromatic aberrations.

- Optics: always consisted by a set of cylindrical lenses and mirrors to shape the light source beam into a planar sheet to illuminate the flow field





Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Perform a PIV ?

The laser used are usually in Class 4

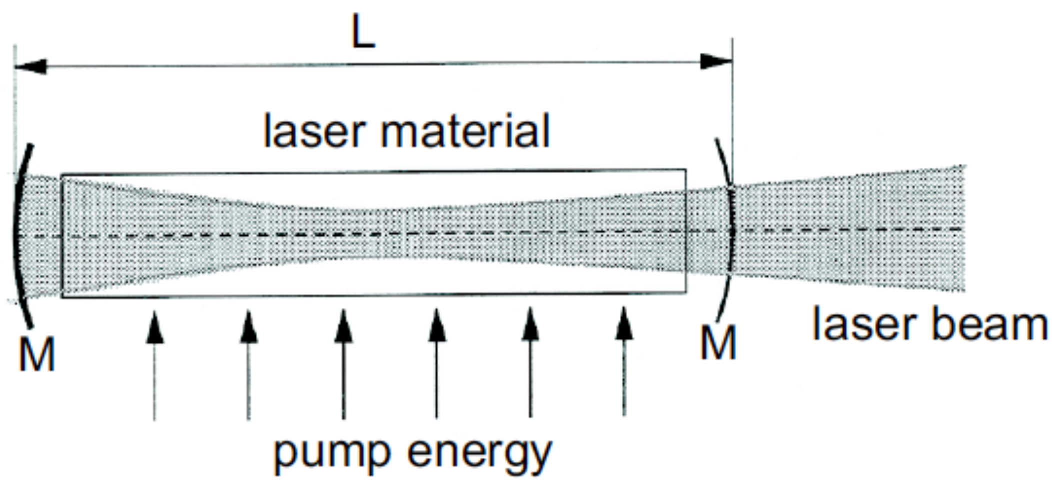
High power devices; hazardous to the eyes (especially from reflected beam) and skin; can be also a fire hazard

- 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.

Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Perform a PIV ?

Trigger a laser beam



Every laser consists of three main components: **a laser material**, **a pump source** and an oscillator. **The pump usually is** a krypton **flashlamp.**

- Seeding
- Illumina.
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- Selection
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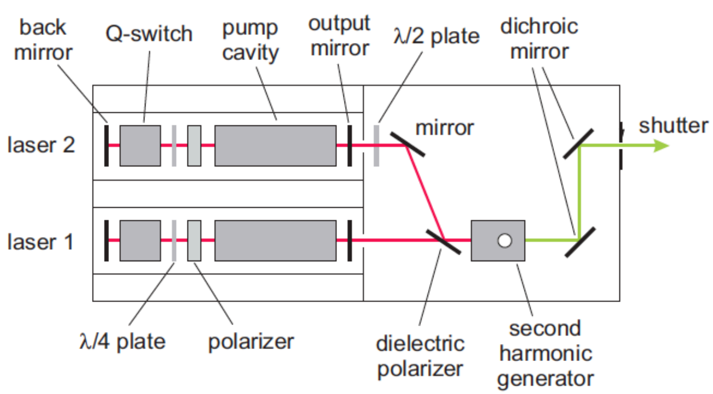
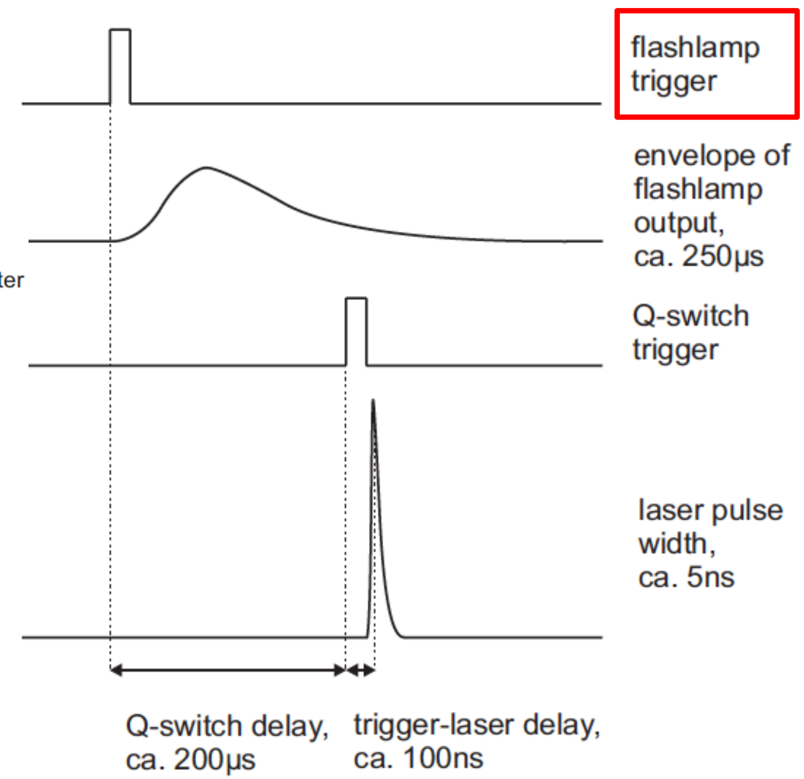
- Estimation

Perform a PIV ?

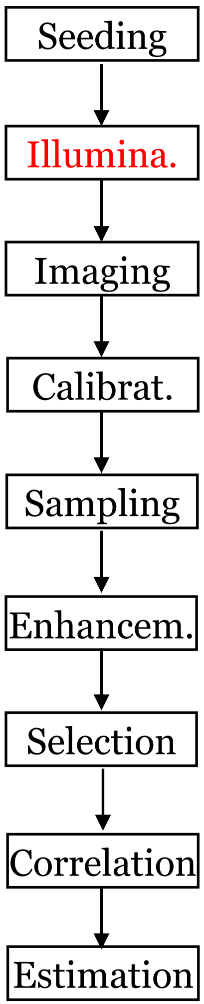
Trigger a laser beam



Typical layout of a dual oscillator Nd:YAG.

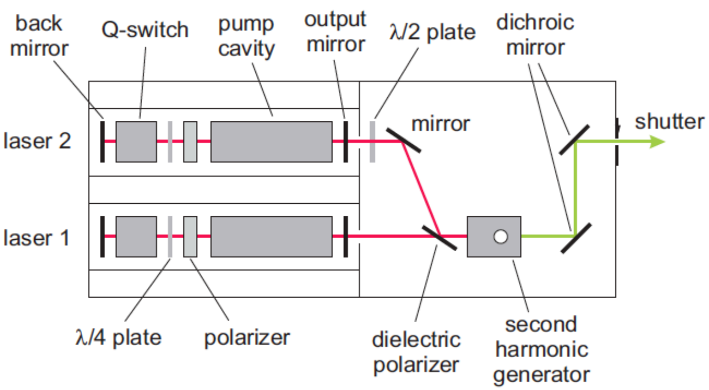


Time series of triggering a laser pulse



Perform a PIV ?

Trigger a laser beam



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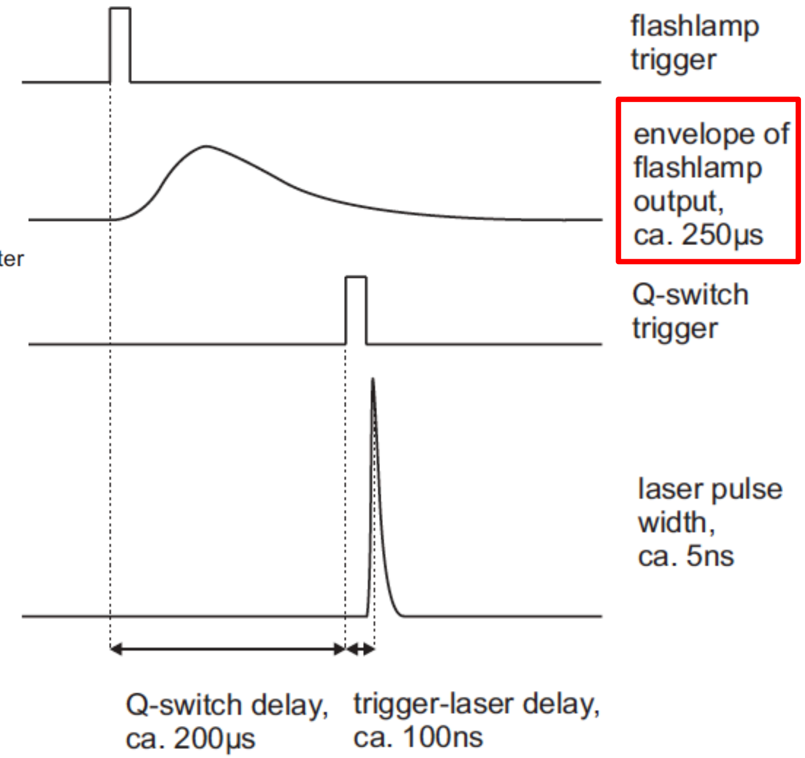

Time series of triggering a laser pulse

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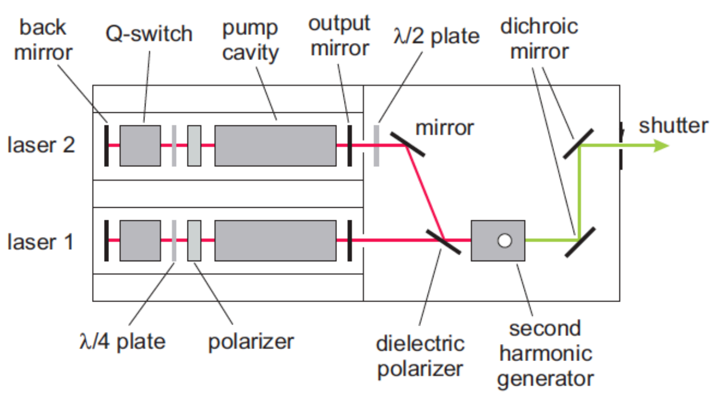
Trigger a laser beam



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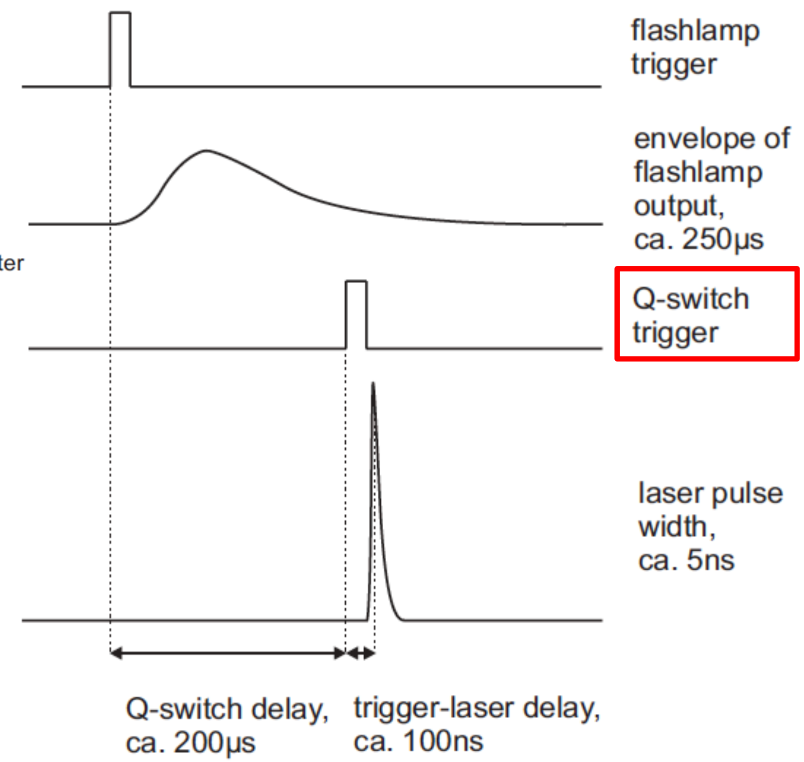

Time series of triggering a laser pulse

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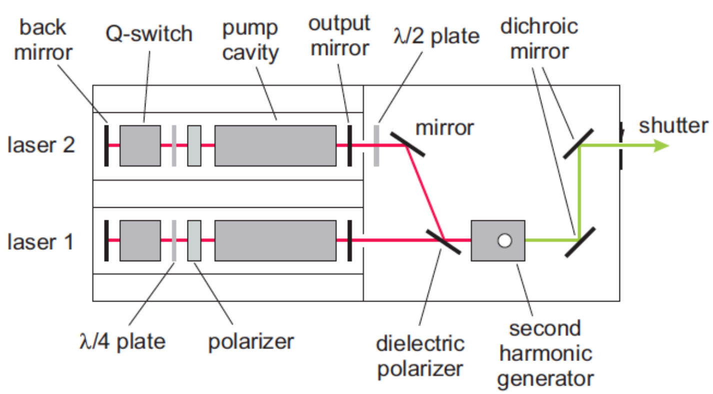
Perform a PIV ?

Trigger a laser beam



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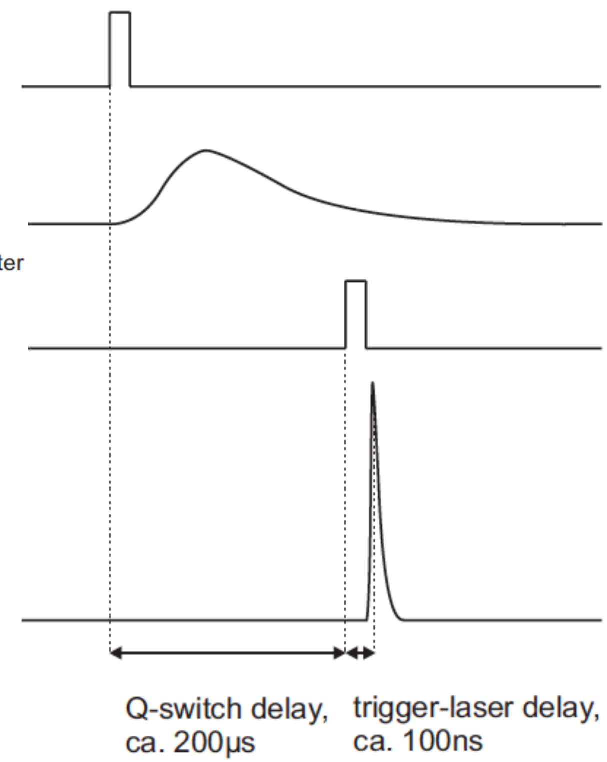


Time series of triggering a laser pulse

Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Perform a PIV ?

Power & frequency

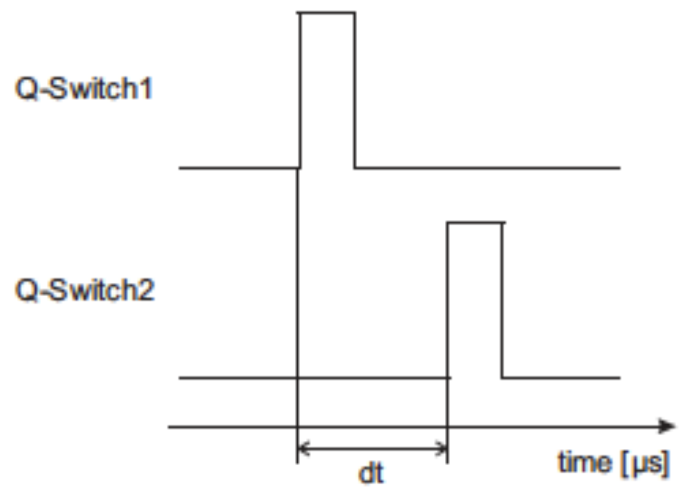
- A large amount of light (from 20 mJ to 400 mJ) must be available in a short time (~ 5ns).
- Inter-pulse (Δt) timing may vary from less than 1μs to many ms depending upon the velocity of the flow.
- The repetition rate of a pulsed laser is typically 10-30Hz
- Adequate only for velocities < 1 m/s

- 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.

Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Perform a PIV ?

Pulse separation



The possible range for the *dt* depends on the camera (min. interframe time or max. reprate), the acquisition mode and the type of laser.

Seeding
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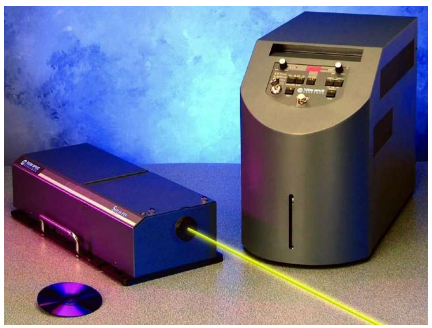
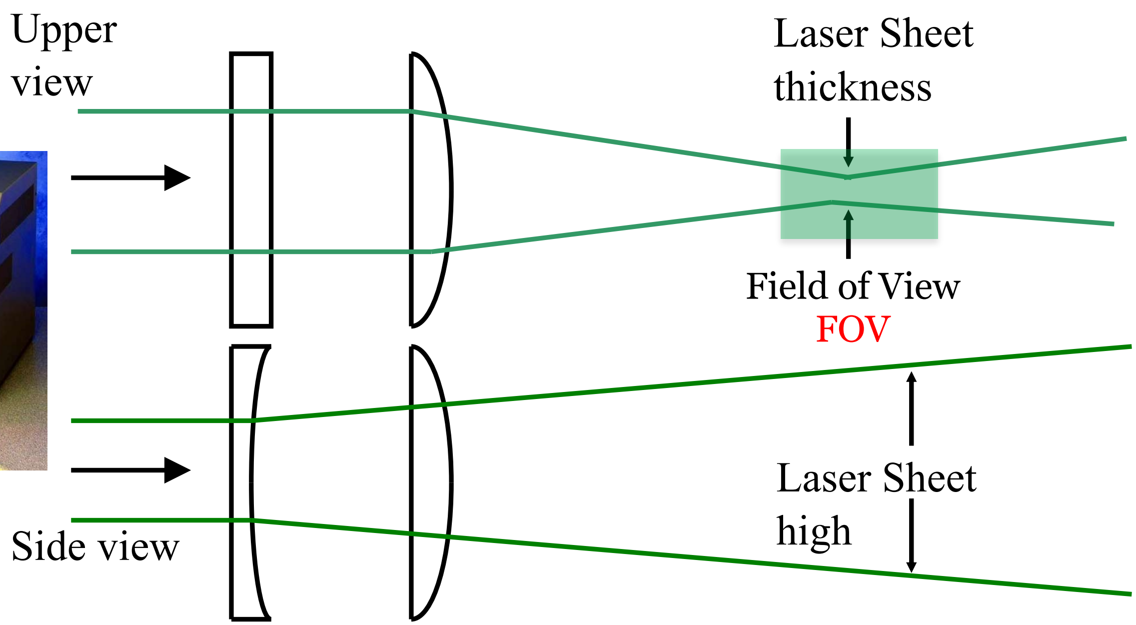
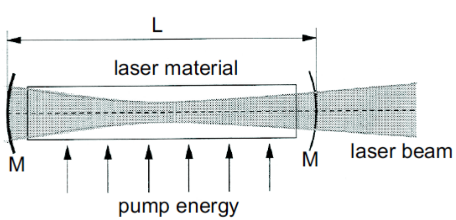
Perform a PIV ?

Laser Sheet







Seeding → **Illumina.** → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Perform a PIV ?

CCD & CMOS sensors

Cameras based on a **CCD** (Charge Coupled Device) or **CMOS** (Complementary Metal-Oxide Semiconductor) sensor with high resolution and high sensitivity are commonly used in PIV.

The biggest difference is that CCD sensors create high quality images with low noise (grain). CMOS images tend to be higher in noise. **CCD sensors are more sensitive to light**. CMOS sensors need more light to create a low noise image at proper exposure.

Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

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CCD camera specs

Category	ProSX 5M
art. no.	1101396
double shutter	two images with 600 ns min. interframing time
resolution (h$\times$v)	2448 pixel$\times$2050 pixel
sensor type	Sony ICX625
optical size	2/3”
pixel size	3.45 $\mu m \times$3.45 μm
spectral range	400 - 850 nm
full well capacity	7,000 e^2
max. QE	52% @ 500 nm
max. frame rate (at full resolution)	14.2 fps
noise	13 e^-
binning	yes
partial scan	yes
data output type	Gigabit ethernet (1000 Mbits/s)
ADC bit depth	12 bit
synchronization	via ext. trigger
exposure control	programmable
power requirements	+12 to +24 VDC, $\leq$1% ripple
	$\leq$5 W @ 12 V
I/O ports	2 opto-isolated input ports and 4 opto-isolated output ports
lens adapter	CS mount
operating temperature	5 - 40 °C
size (l x w x h)	100 mm$\times$57 mm$\times$45 mm (without lens adapter or connectors)
weight	380 g
conformity	CE, FCC, ROHS, IP30

Seeding → Illumina. → **Imaging** → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Perform a PIV ?

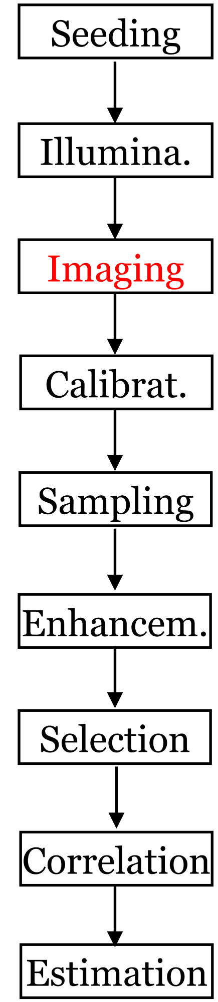
CCD camera specs – resolution in pixels

512 x 512

128 x 128

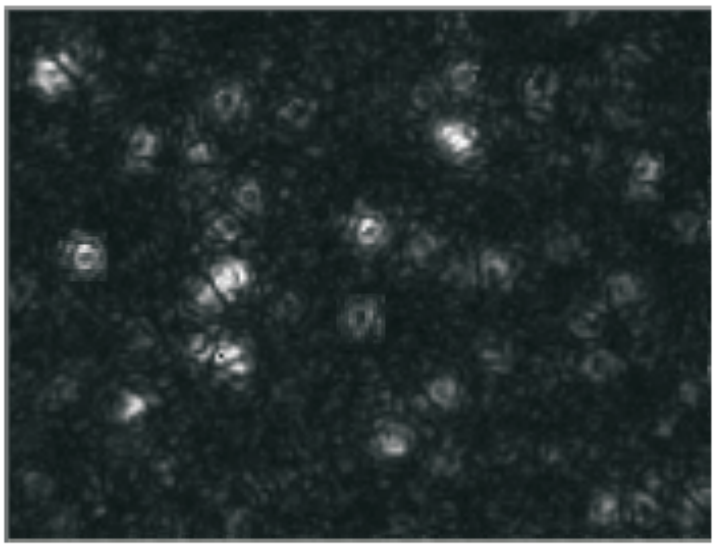
64 x 64

32 x 32

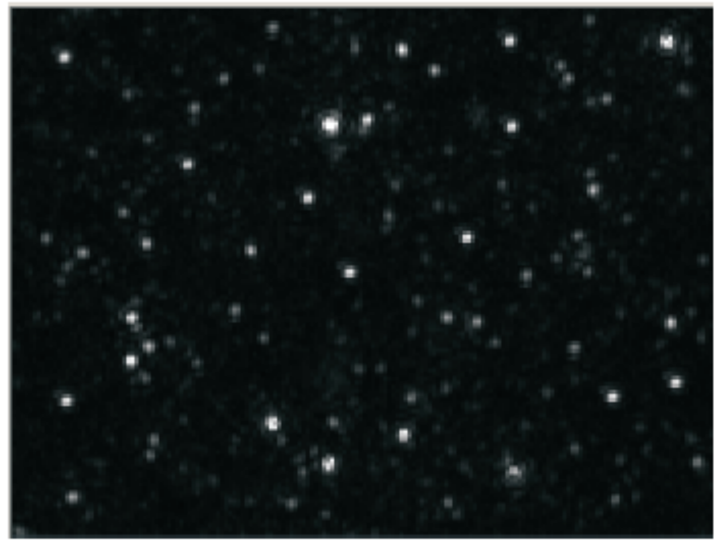


Perform a PIV ?

CCD camera specs – resolution in pixels



Blurred particle image



focused particle image

Seeding → Illumina. → **Imaging** → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Perform a PIV ?

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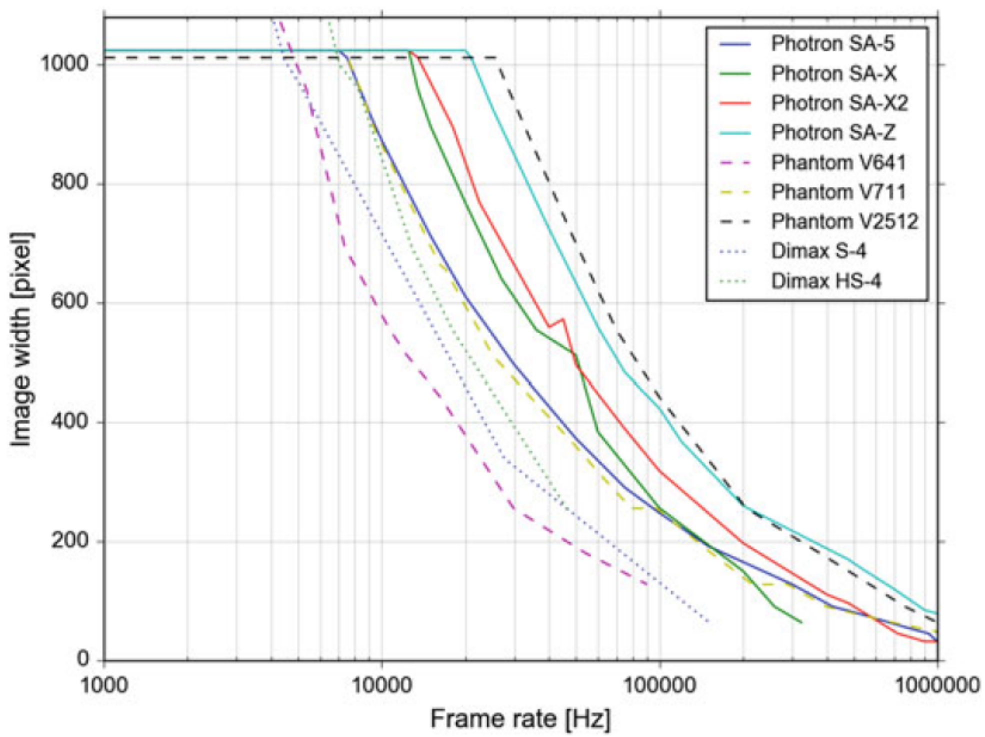
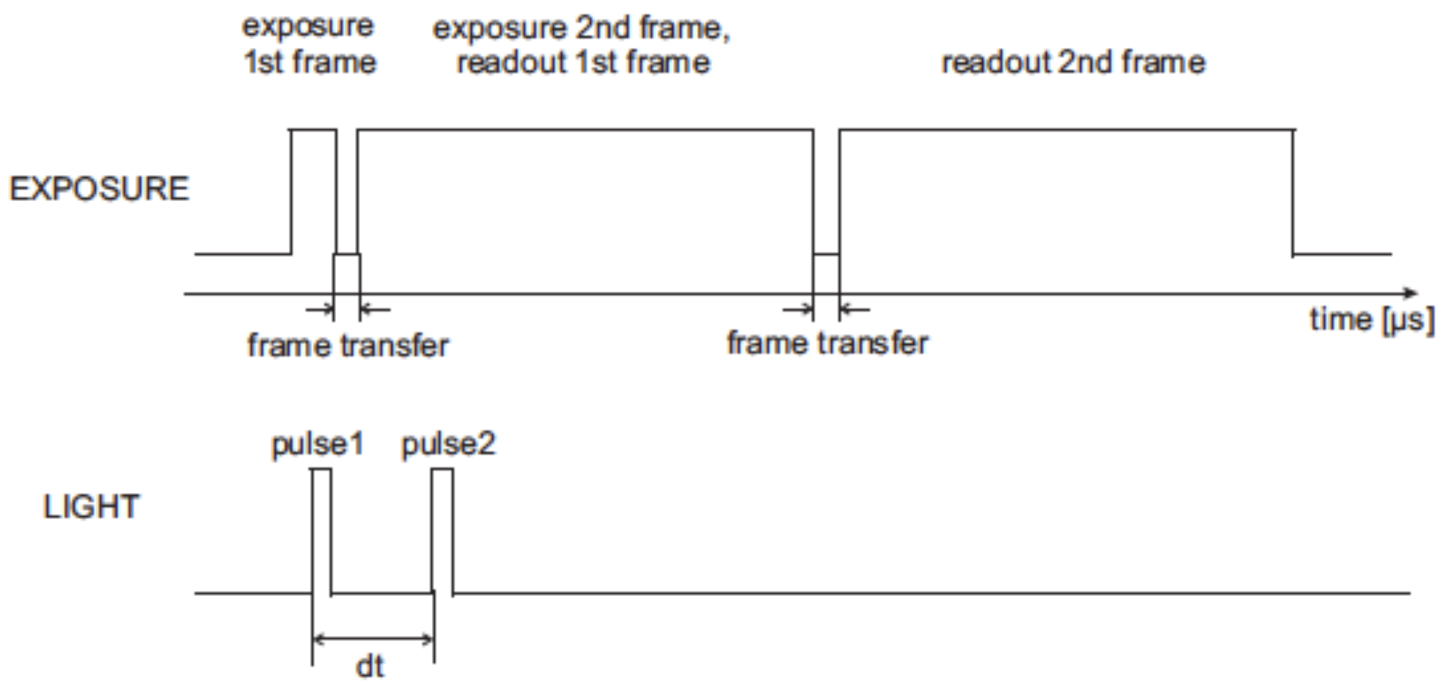
CCD camera specs – frame rate

- High frame rates, together with the relatively high spatial resolution needed for most PIV applications result in a large amount of data that has to be transferred from the chip into storage.
- This requires high clock speeds and, as a consequence, a high bandwidth of the read out electronics. The high bandwidth of the sensor increases the noise while the efficiency decreases.
- Those problems resulted in sensor designs, in which the sensor is divided into smaller segments, which are read out in parallel (much like parallel computing).



Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

CCD camera specs – timing scheme



Timing scheme for a double frame recording

CCD camera specs – timing scheme

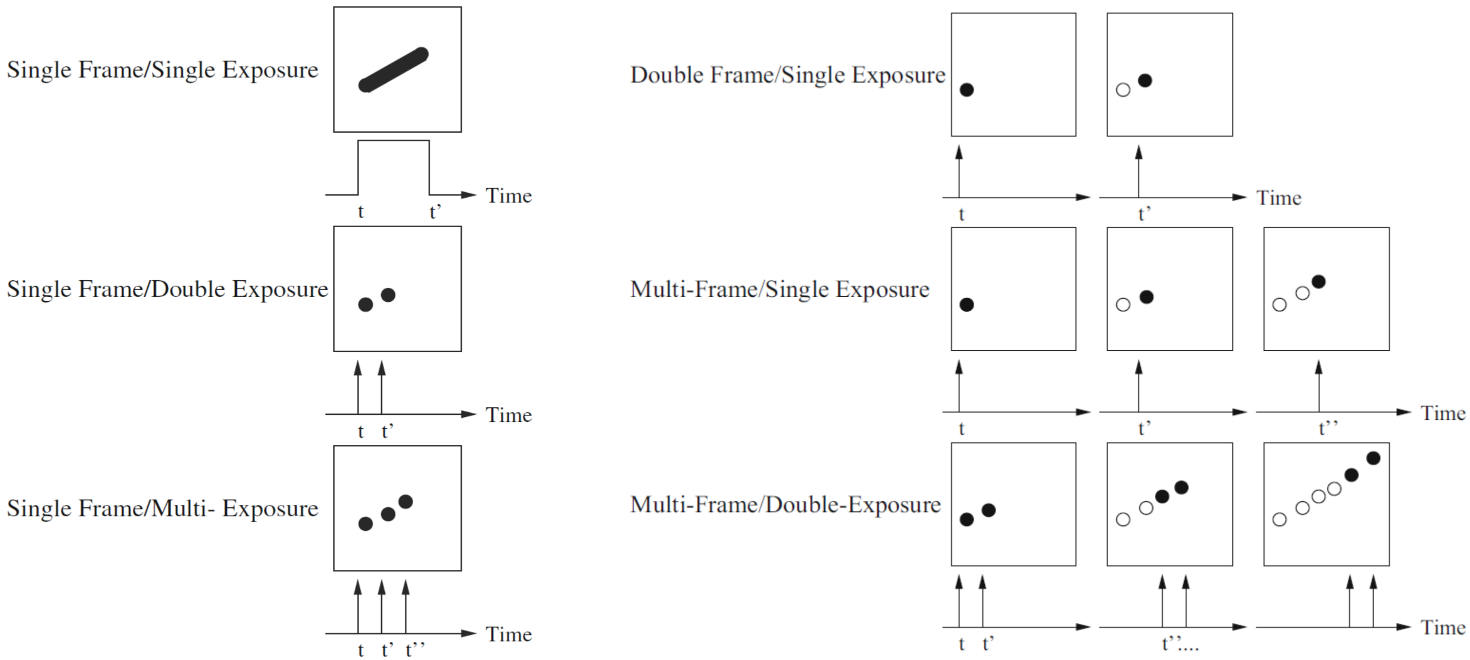
The exposure times for first and second frame of a recording in a double frame mode are extremely different. Usually the **exposure time for the first frame is in the range of some microseconds**, while the time for the **second exposure** is **determined by the time needed for the read out** of the first exposure what goes with the camera repetition rate. Typically this is in the **order of hundred milliseconds**. To get rid of the different background in a double exposure due to the different exposure times a suitable bandpass filter is used in front of the camera lens. This makes sure that only the light of a certain wavelength can reach the CCD and the unwanted background light is suppressed. So actually the length of the laser pulse determines the effective exposure time.

Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Perform a PIV ?

CCD camera – recording mode

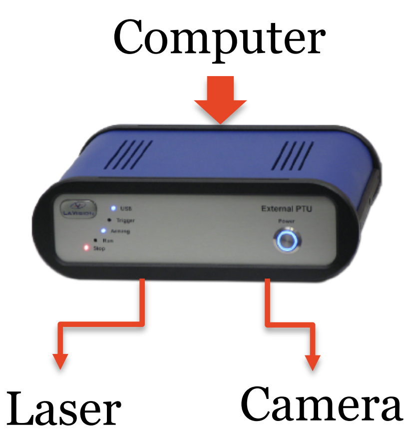
- Two major recording modes are used in PIV
  a) Single Frame/Double Exposure *or* Single Frame/Multi Exposure
  b) Double Frame/Single Exposure *or* Multi Frame/Single Exposure
- The choice depends on:
  a) Desired spatial or temporal resolution; b) Required accuracy

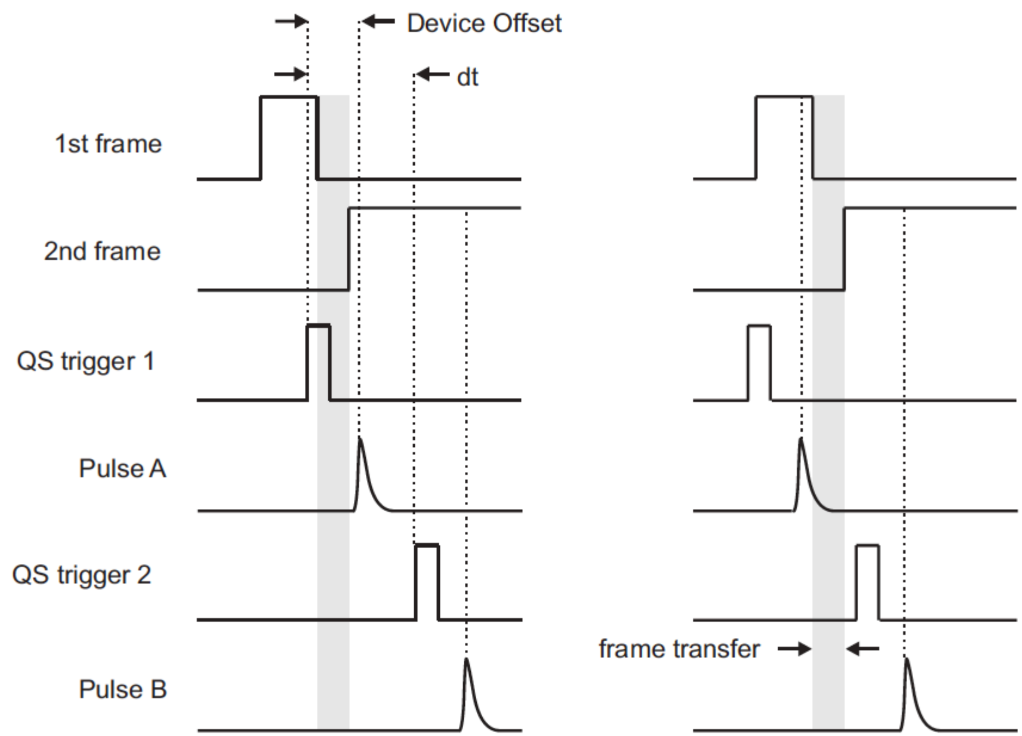


Seeding → Illumina. → **Imaging** → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Perform a PIV ?

Synchronize laser & cameras





Which is a correct timing scheme
for a double-frame recording?

Seeding
↓
Illumina.
↓
Imaging
↓
Calibrat.
↓
Sampling
↓
Enhancem.
↓
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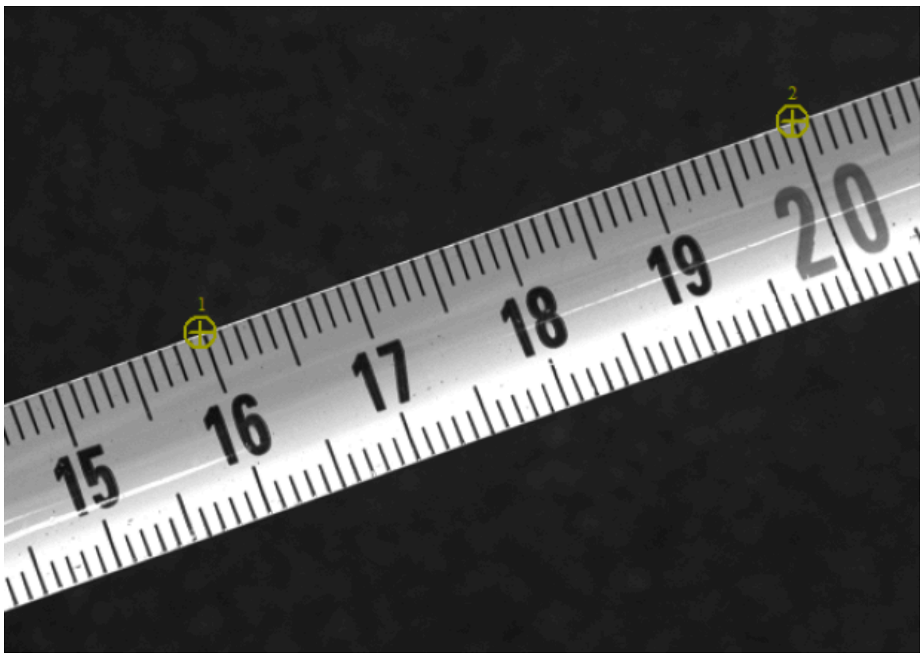
Perform a PIV ?

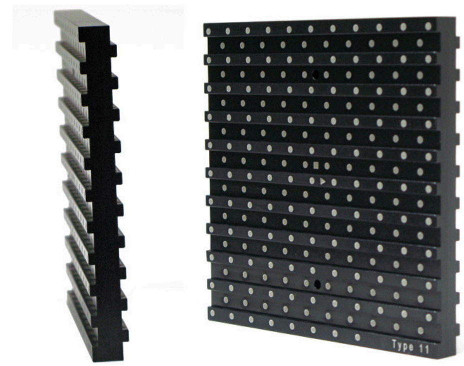
Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

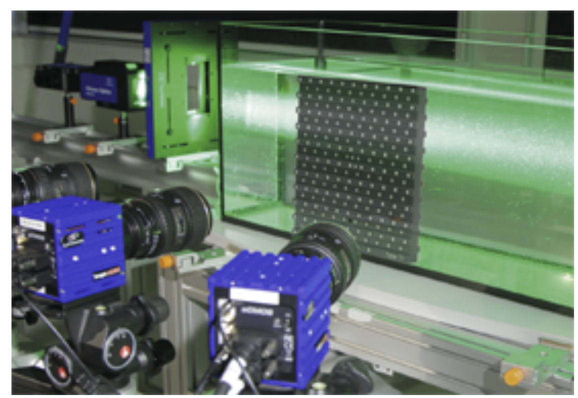
Perform a PIV ?

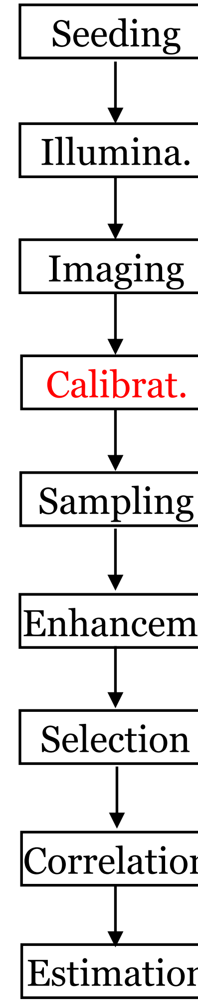
Calibration – pixel to mm



Pixel / mm

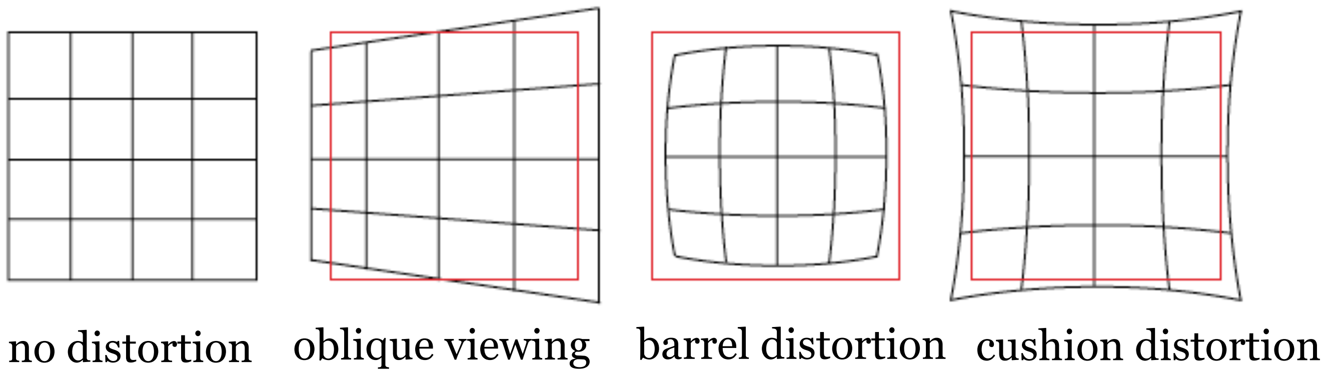


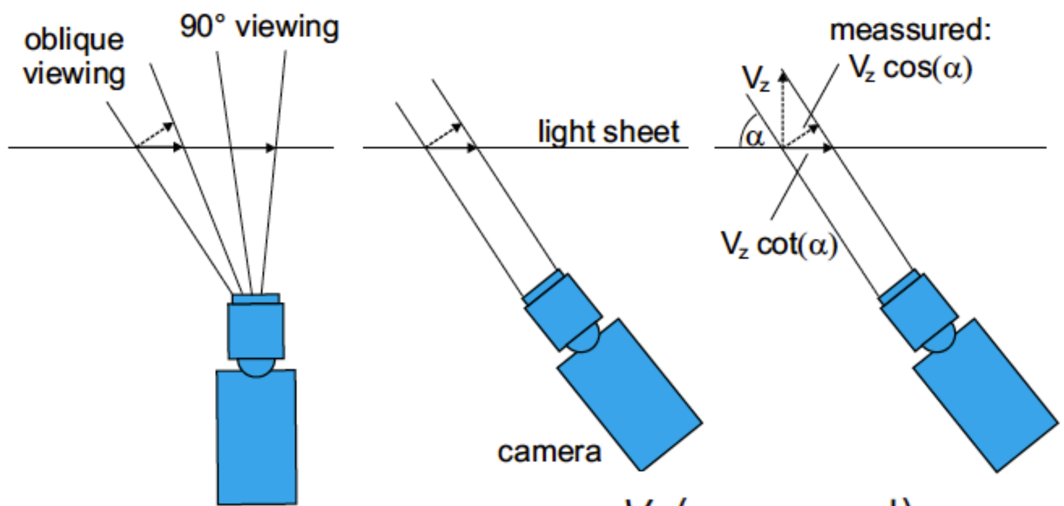




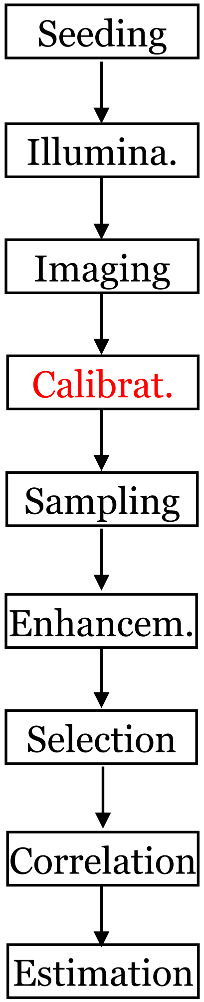
Perform a PIV ?

Calibration - distortion





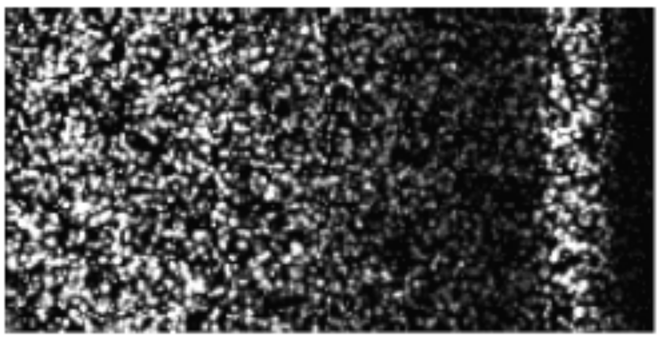
$$V_x(\text{true}) = \frac{V_x(\text{measured})}{\sin(\alpha)}.$$



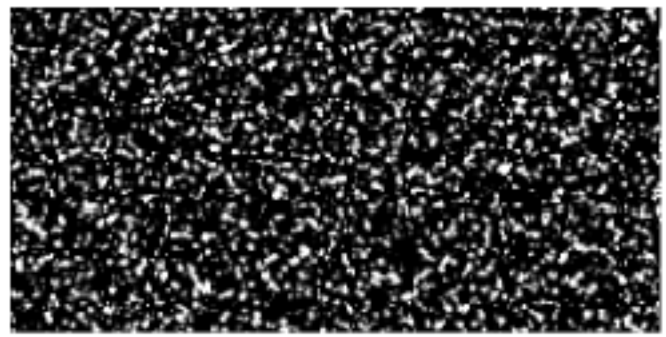
Perform a PIV ?

Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Subtract a sliding background



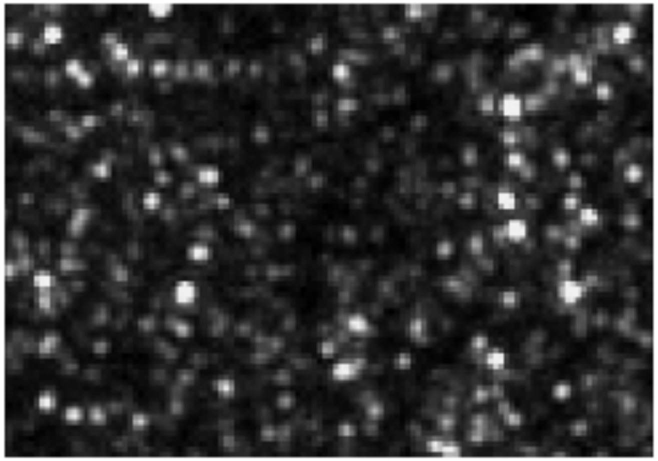
Original particle image



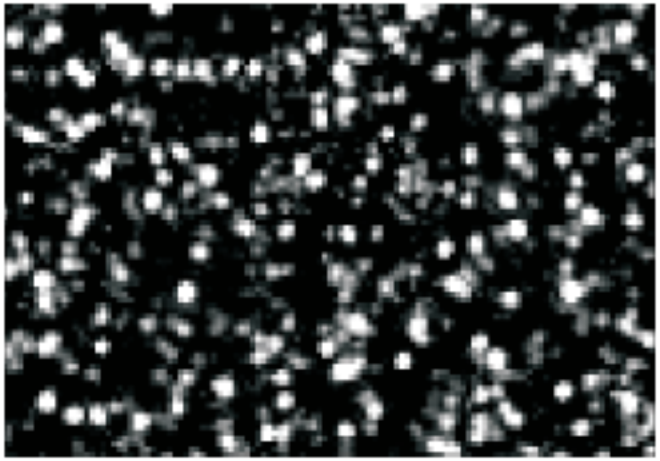
After sliding background filter

Perform a PIV ?

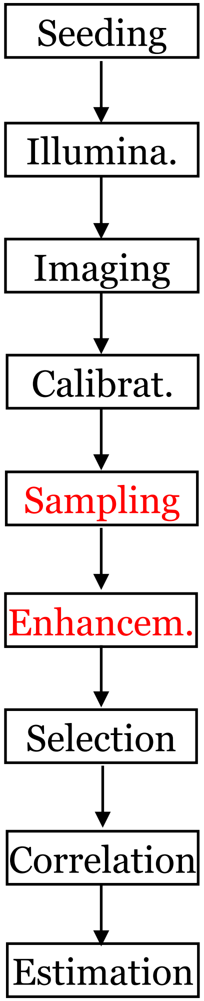
Particle intensity normalization
(min/max-filter)



Original particle image



After normalization



Process PIV Data

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Seeding
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Correlation
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Process PIV Data

- PIV recordings are subdivided into **interrogation "windows"**
- Instead of the distance travelled by the individual objects, the **displacement of the interrogation window**, in two subsequent images taken with a time interval Δt, is calculated
- The ratio of displacement and time interval gives the **velocity of a single interrogation window**
- The velocity of **each interrogation window** is calculated to **generate the flow field**
- The displacement of the interrogation window is calculated by **auto-correlation** or **cross-correlation**

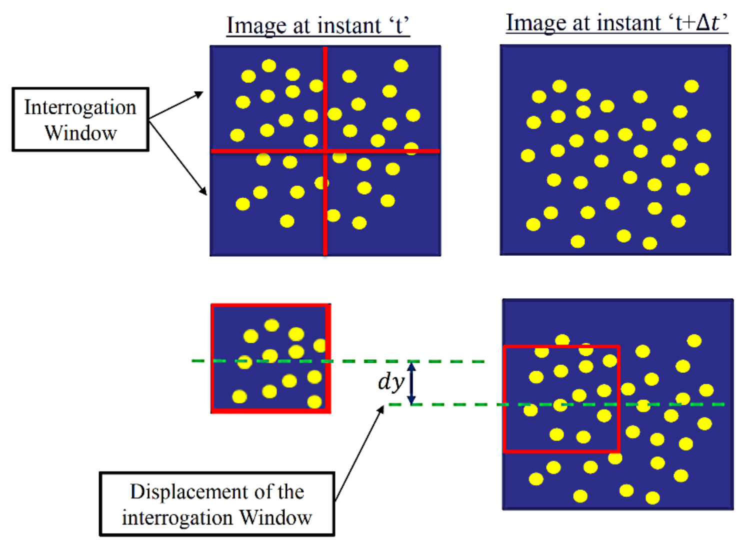

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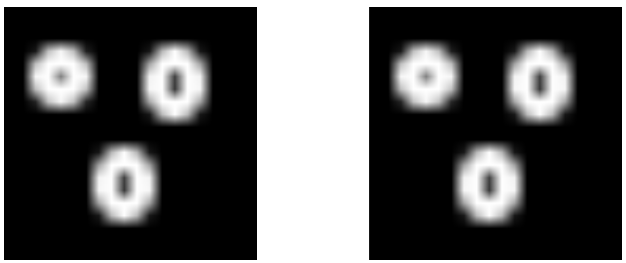
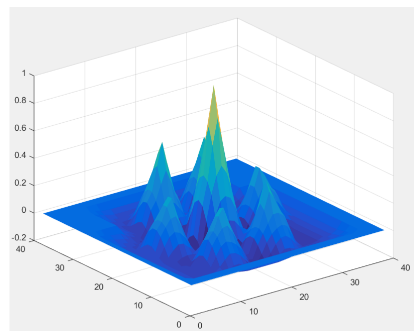
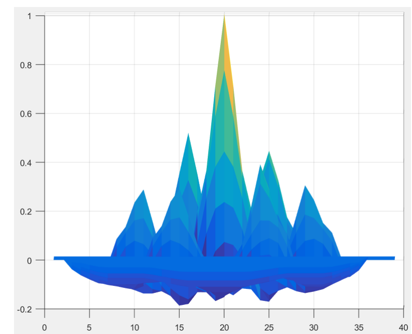
Image correlation

- In PIV, the images are taken with some time interval Δt, which results in displacement of particle in subsequent images.
- The correlation of these subsequent images results in a shift for peak intensity (away from the centre). This shift corresponds to the displacement of the particles.

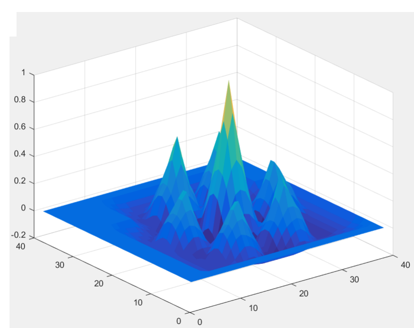


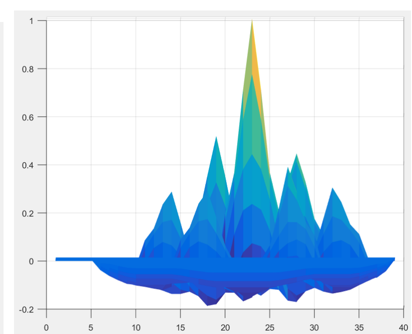
Correlation of an image with itself results in a peak in centre





Correlation of an image with subsequent image, having displaced particles results in a peak away from the centre





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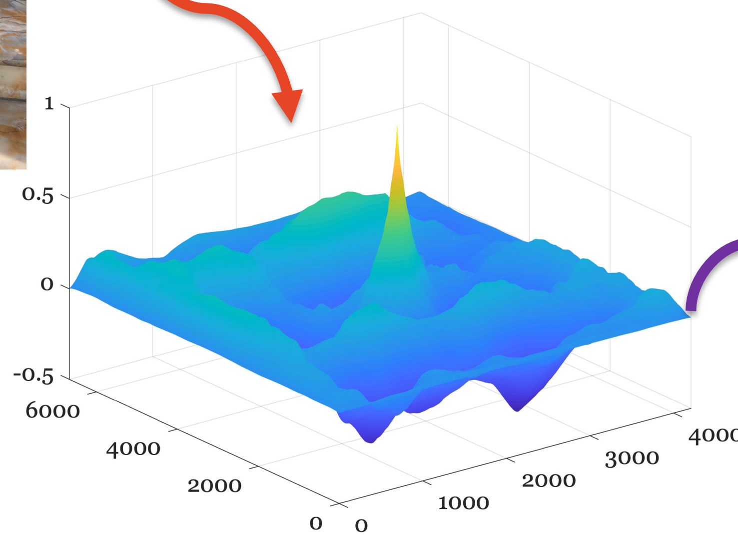
Process PIV Data

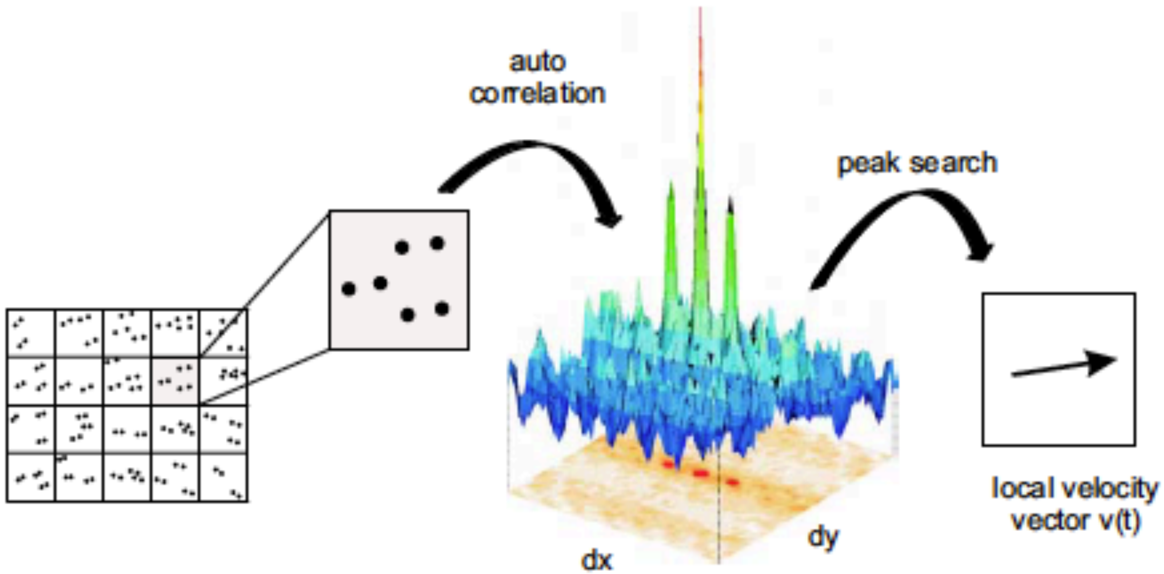
Interrogation window recogn.



Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhance. → Selection → Correlation → Estimation

Process PIV Data

Auto-correlation



The scattered light from first and second exposure of the particles is recorded in **one image**. The complete image is subdivided in so called interrogation window and each window is evaluated by auto correction.

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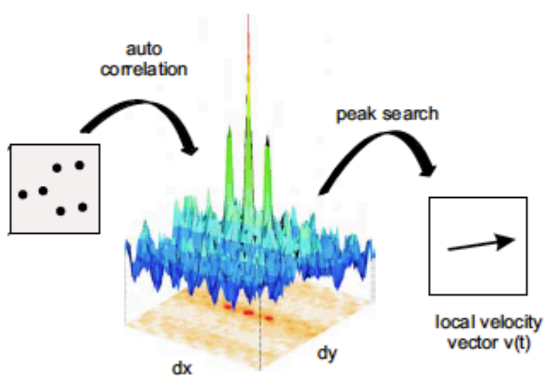
Process PIV Data

Auto-correlation

The auto-correlation is characterized by two identical correlation peaks rotationally symmetrical about the highest central peak indicating zero displacement. This is a consequence that the sign of the displacement can not be determined, because **we do not know which particles are illuminated by the first and the second laser pulse**. So the information from the autocorrelation is ambiguous and not conclusive if you can not use some a priori information about the observed flow. Also the detection of very small displacements is a problem as in this case the correlation peaks are very close to the central peak.

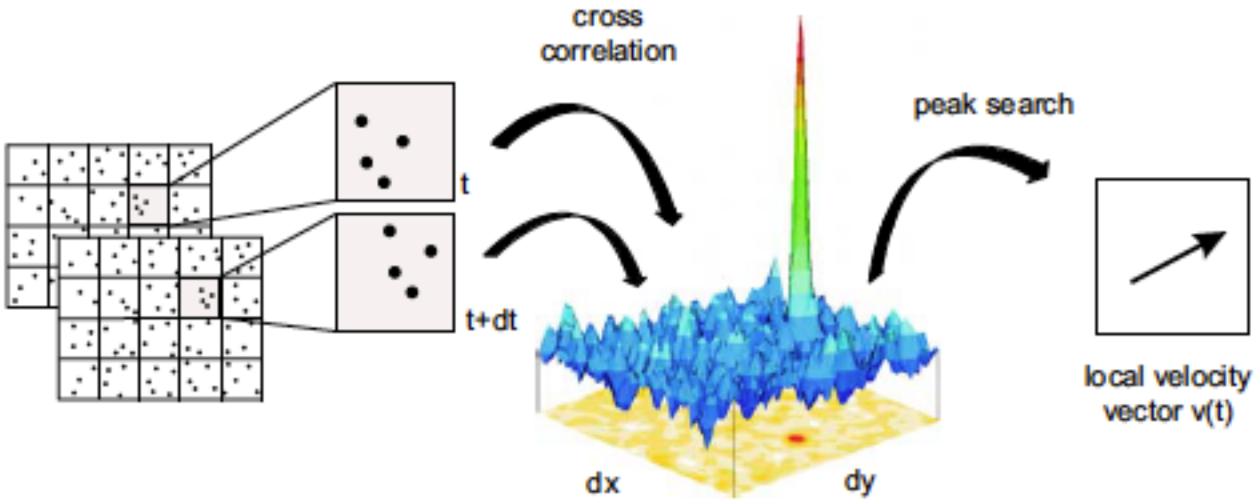


Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Process PIV Data

Cross-correlation

The scattered light from first and second exposure of the particles is recorded in **two different images**. The complete image is subdivided in interrogation windows and each window is evaluated by cross correction.



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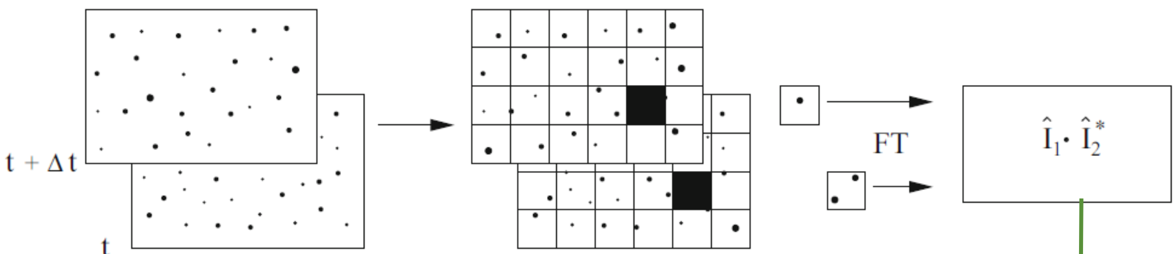
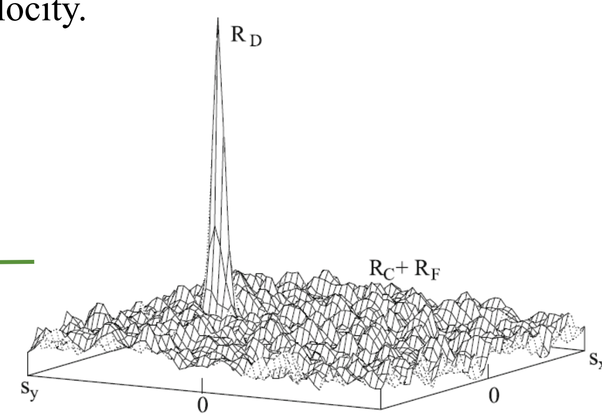
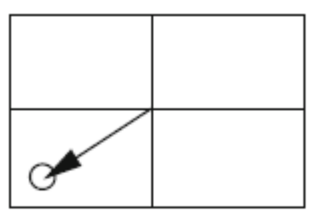
Process PIV Data

Cross-correlation



In double frame/single exposure method the **location of the correlation peak gives the displacement** of the interrogation window, which is utilised to get both the magnitude and direction of the flow velocity.





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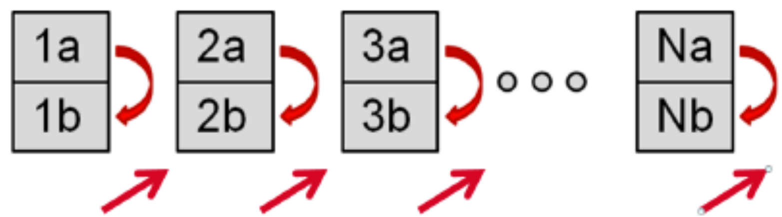
Process PIV Data

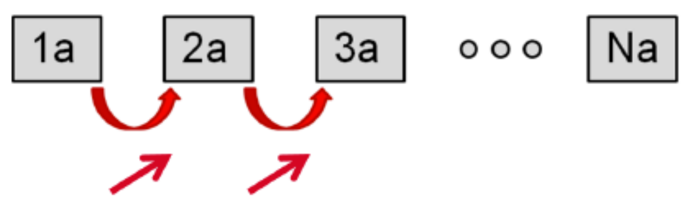
Image-pair for cross-correlation

Double-frame images

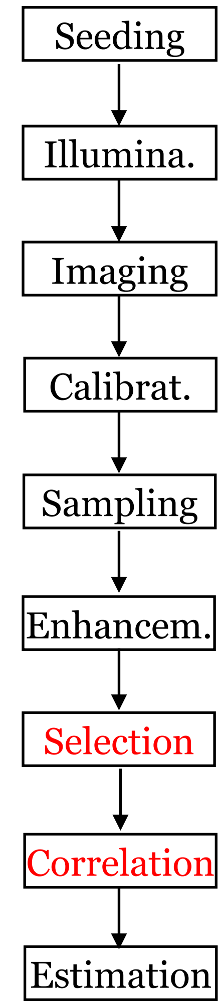


In this case the cross-correlation will work on the two frames of one recording.

Single-frame images



In this case the cross-correlation will work on the two consecutive frames of one recorded time-series.



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Process PIV Data

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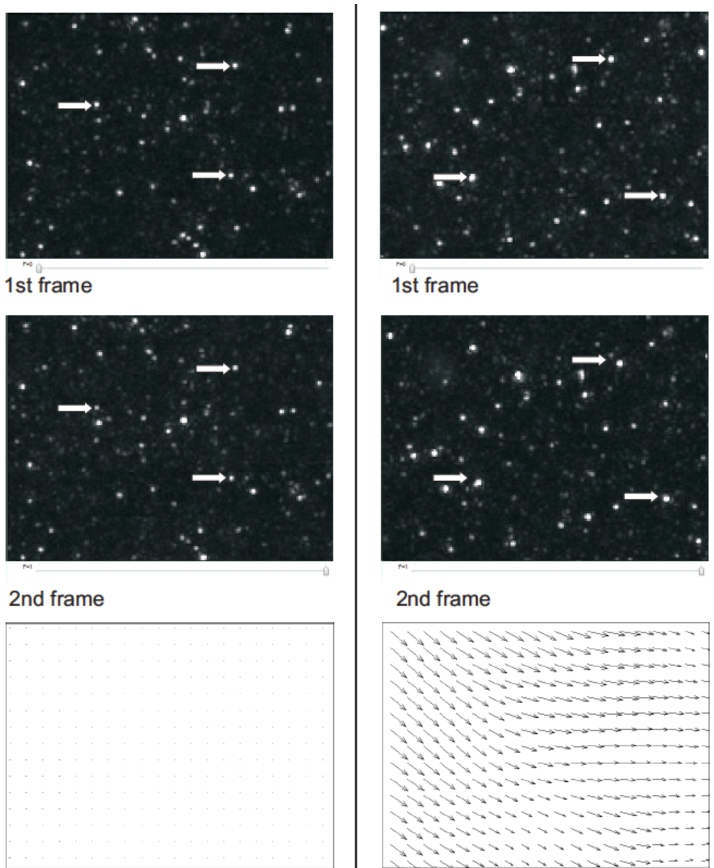
Interrogation window size



particle displacement <0.1 pixel

particle displacement ~5 pixel

For a given flow velocity and factor of magnification the selected pulse delay *dt* determines the separation *ds* of the particle images on the CCD. The optimum separation of particle images depends on the desired interrogation window size and on the velocity gradients in the PIV recording.

In general for cross-correlation the separation of the particle images (in pixel) should be larger than the accuracy of the peak detection and smaller than a quarter of the selected interrogation window size (in pixel):

$$0.1\,px < ds < \frac{1}{4}\,d_{IntWin}$$

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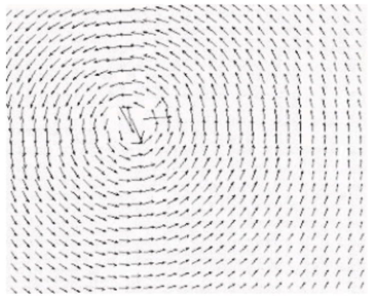
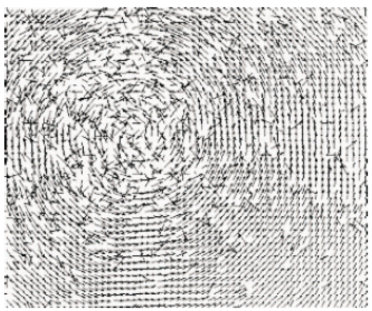
Process PIV Data

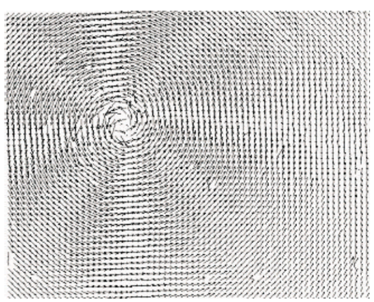
Interrogation window size



Evaluated with a fixed interrogation window size of 16 x 16 pixel



Evaluated with a fixed interrogation window size of 8 x 8 pixel



Evaluated using multi-pass from 32 x 32 pixel down to a final 8 x 8 pixel

Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Process PIV Data

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Iterations

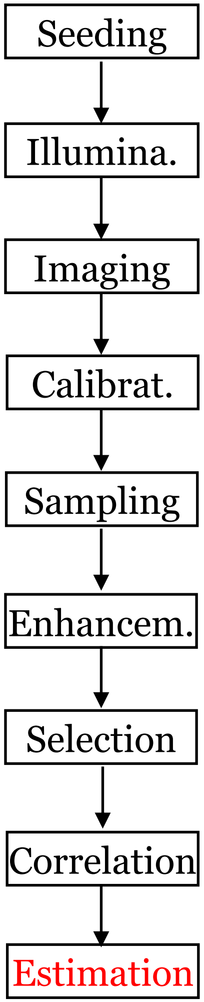
Single pass: The vector calculation is done in one pass. The interrogation window size is constant for the evaluation. There is no postprocessing applied during vector calculation.

Multi pass (constant size): The vector field is calculated by an arbitrary number of iterations Nx on the same image with a constant interrogation window size. In each pass a reference vector for each interrogation window is processed. The computed vector field information is used as reference vector field for the next pass. Using the information of the previous pass the position of the interrogation windows in the new pass is shifted according to the determined particle image shift.

Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

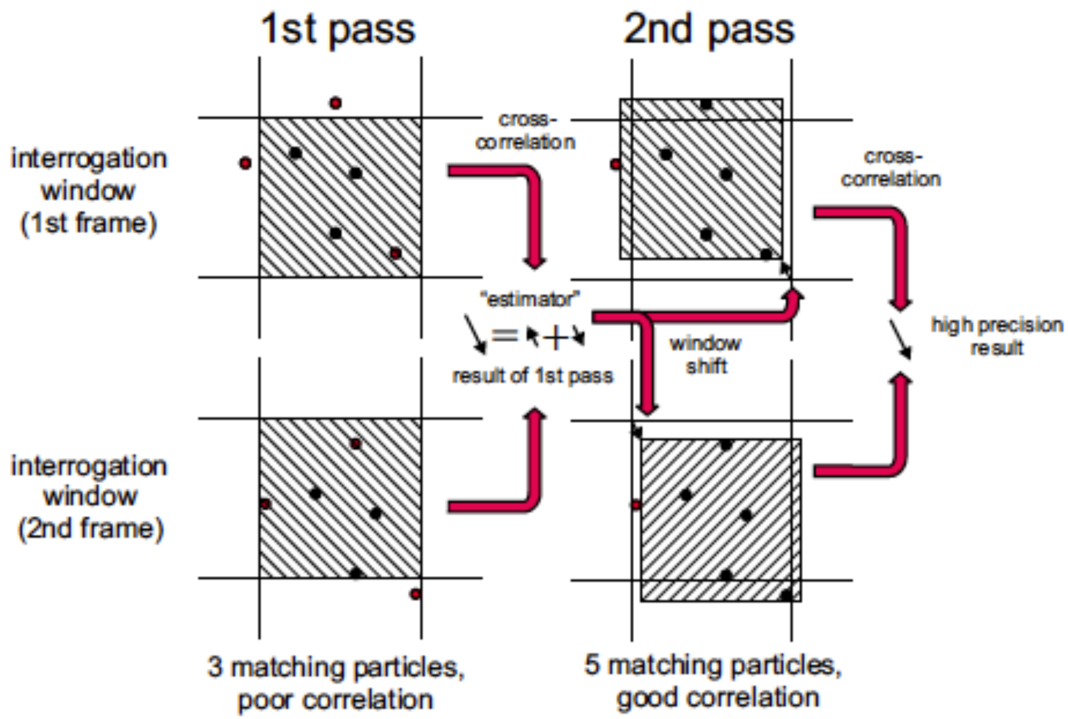
Iterations

Multi pass (decreasing size): The vector field is calculated by an arbitrary number of iterations Nx with a decreasing interrogation window size. The evaluation starts in the first pass with the initial interrogation window size and calculates a reference vector field. In the next pass the window size is half the size of the previous pass and the vector calculated in the first pass is used as a best-choice window shift. In this manner the window shift is adaptively improved to compute the vectors in the following steps more accurately and more reliably. This ensures the same particles are correlated with each other even if you use small interrogation windows where less particles enter into or disappear from the interrogation window.

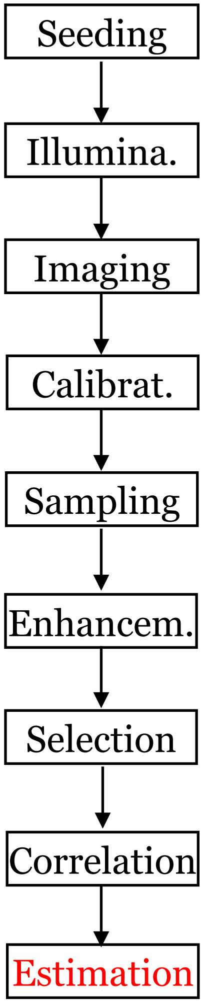


Process PIV Data

Iterations



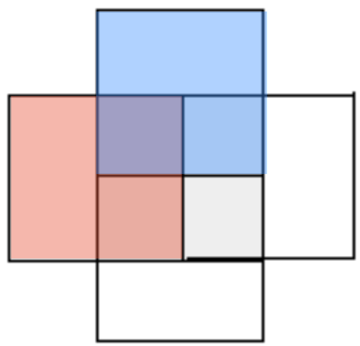
Adaptive multi-pass with constant interrogation window size



Process PIV Data

Overlap

- The Overlap defines the overlap among neighbouring interrogation windows.
- The bigger the specified overlap, the closer is the grid of computed velocity vectors (the number of pixels for each interrogation window is not affected).



Example for 50% interrogation window overlap.

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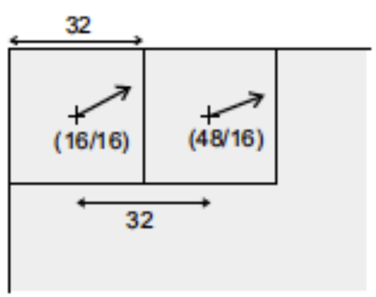
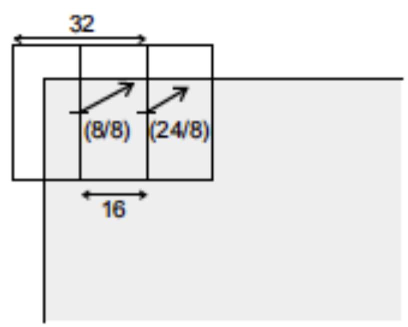
Process PIV Data

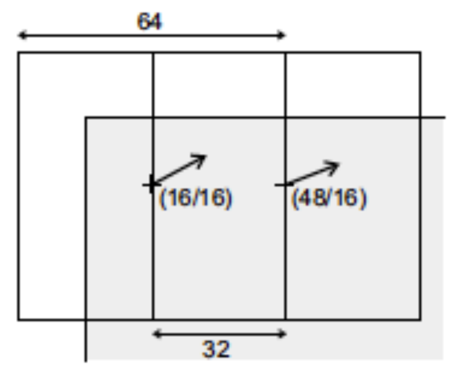
Overlap



Interrogation window: 32 x 32
Overlap: 0%
Grid: 32 pixel



Interrogation window: 32 x 32
Overlap: 50%
Grid: 16 pixel



Interrogation window: 64 x 64
Overlap: 50%
Grid: 32 pixel

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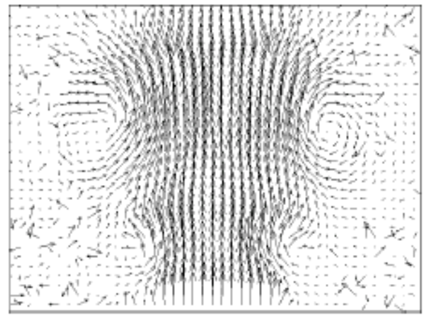
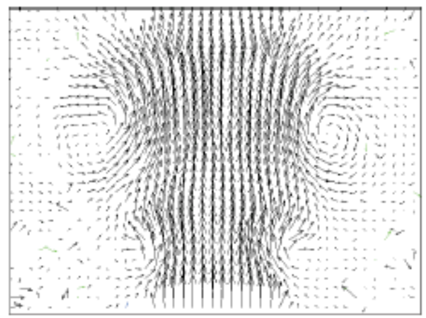
Process PIV Data

Post-processing

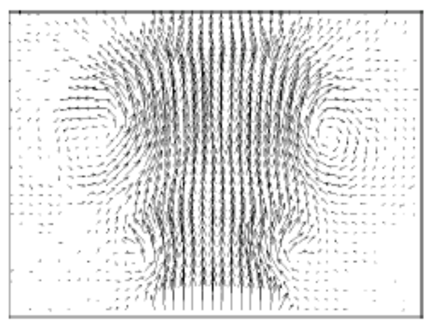
- Allowable vector range
- Median Filter
- Smoothing



Original vector field



+ Median filter

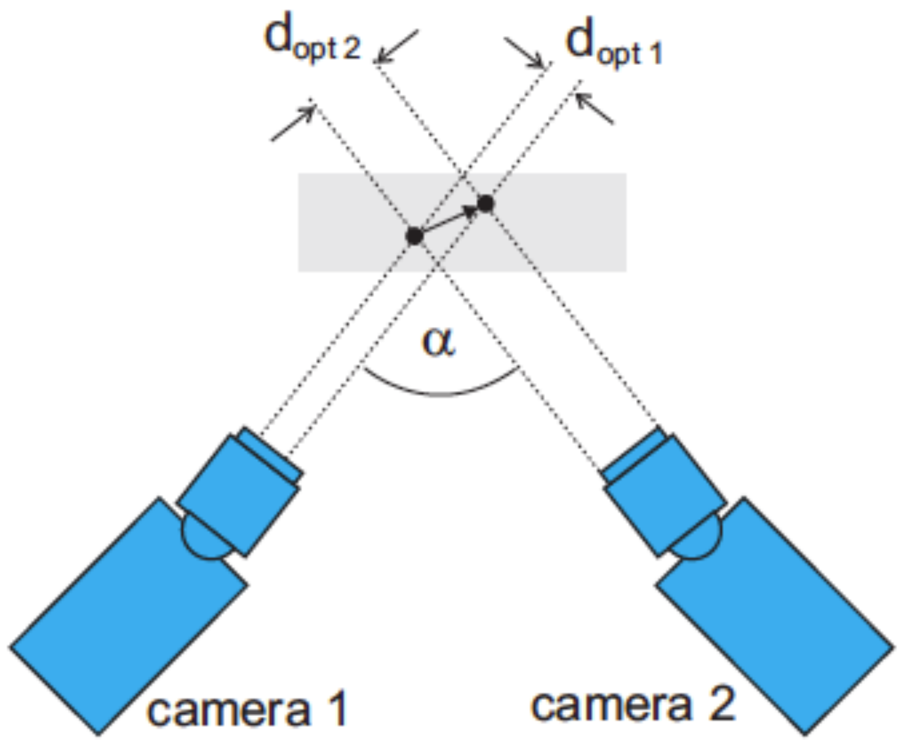


+ Median filter
+ Smoothing

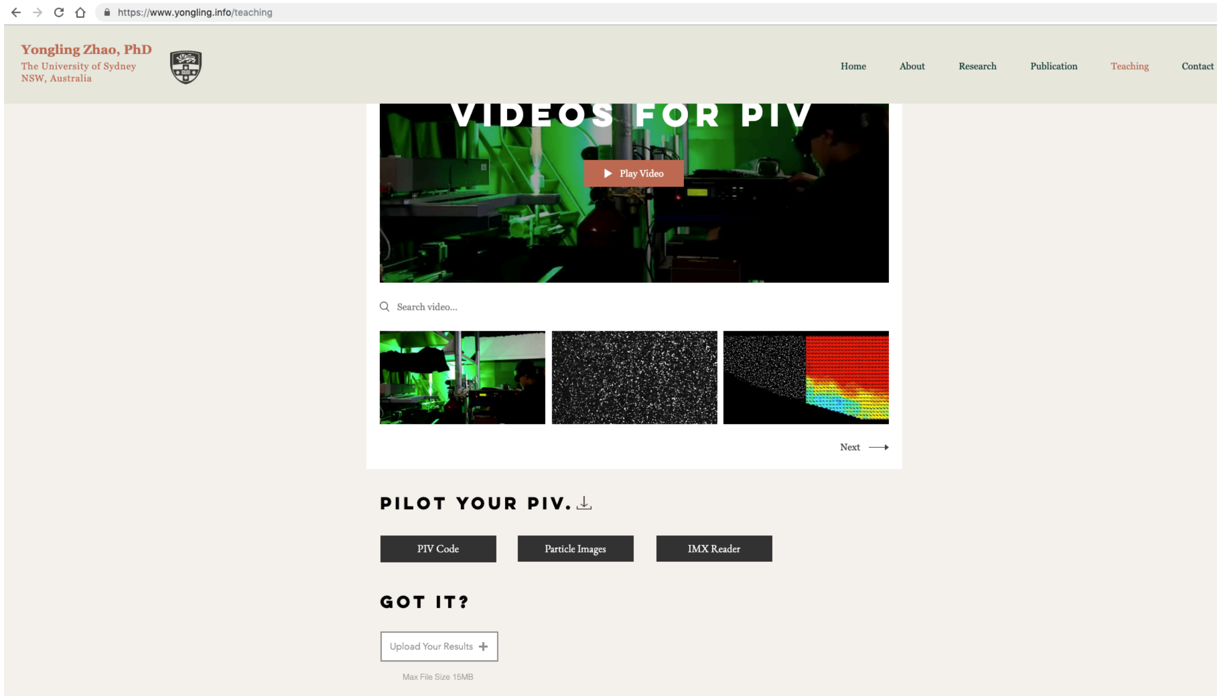
Seeding → Illumina. → Imaging → Calibrat. → Sampling → Enhancem. → Selection → Correlation → Estimation

Further development of PIV

Stereo PIV



Pilot Your PIV



https://www.yongling.info/

- Download particle images
- Download code for correlation
- Upload your results