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Principles of Particle Image Velocimetry (PIV) and case studies

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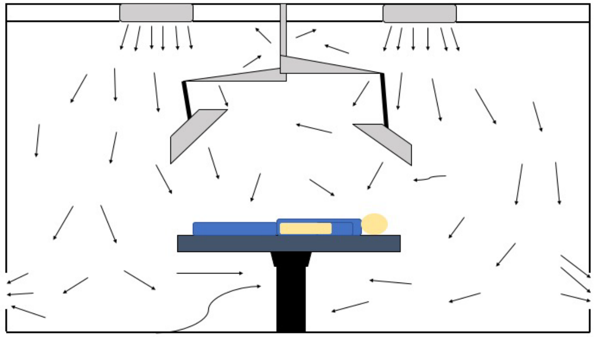
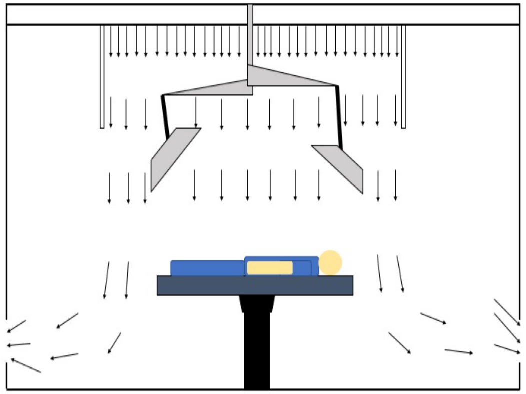
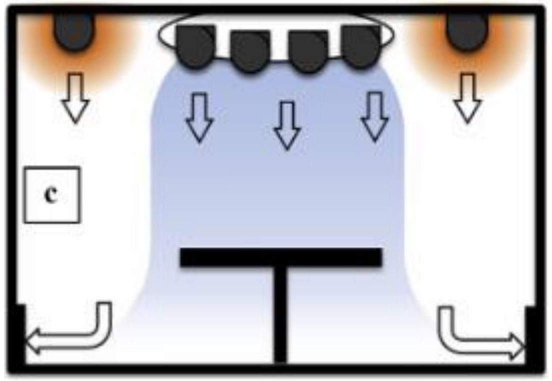
Background - Airflow distribution in operating rooms



Mixing ventilation



Laminar airflow ventilation



Temperature-Controlled Airflow (TAF)

Hybrid impinging airflow

- Allander ventilating system for clean rooms, US patent 3380369, Filed Feb 15, 1966

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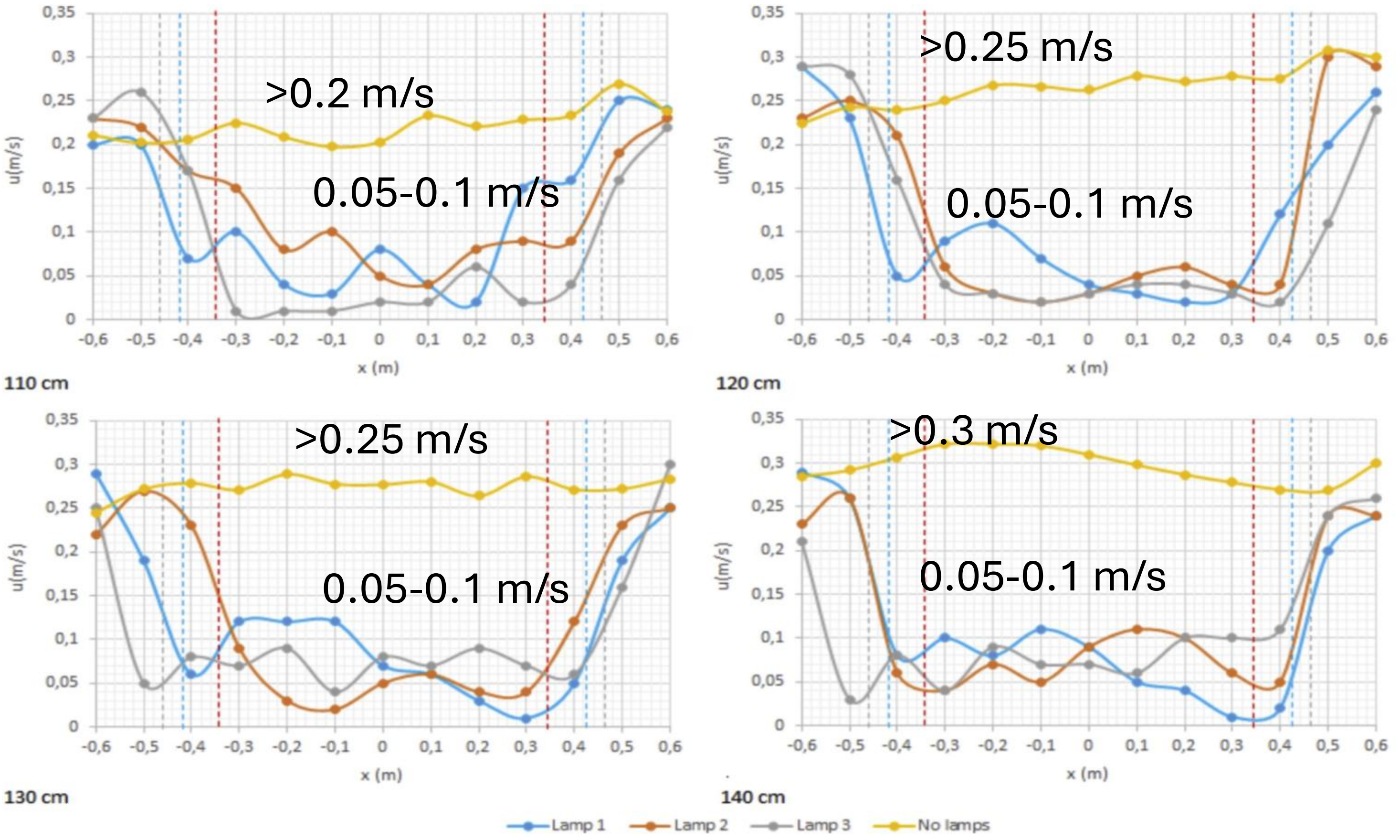
Measured air velocity profiles under surgical lamp in an OR with laminar airflow



Laminar airflow was destroyed under operating conditions !!!

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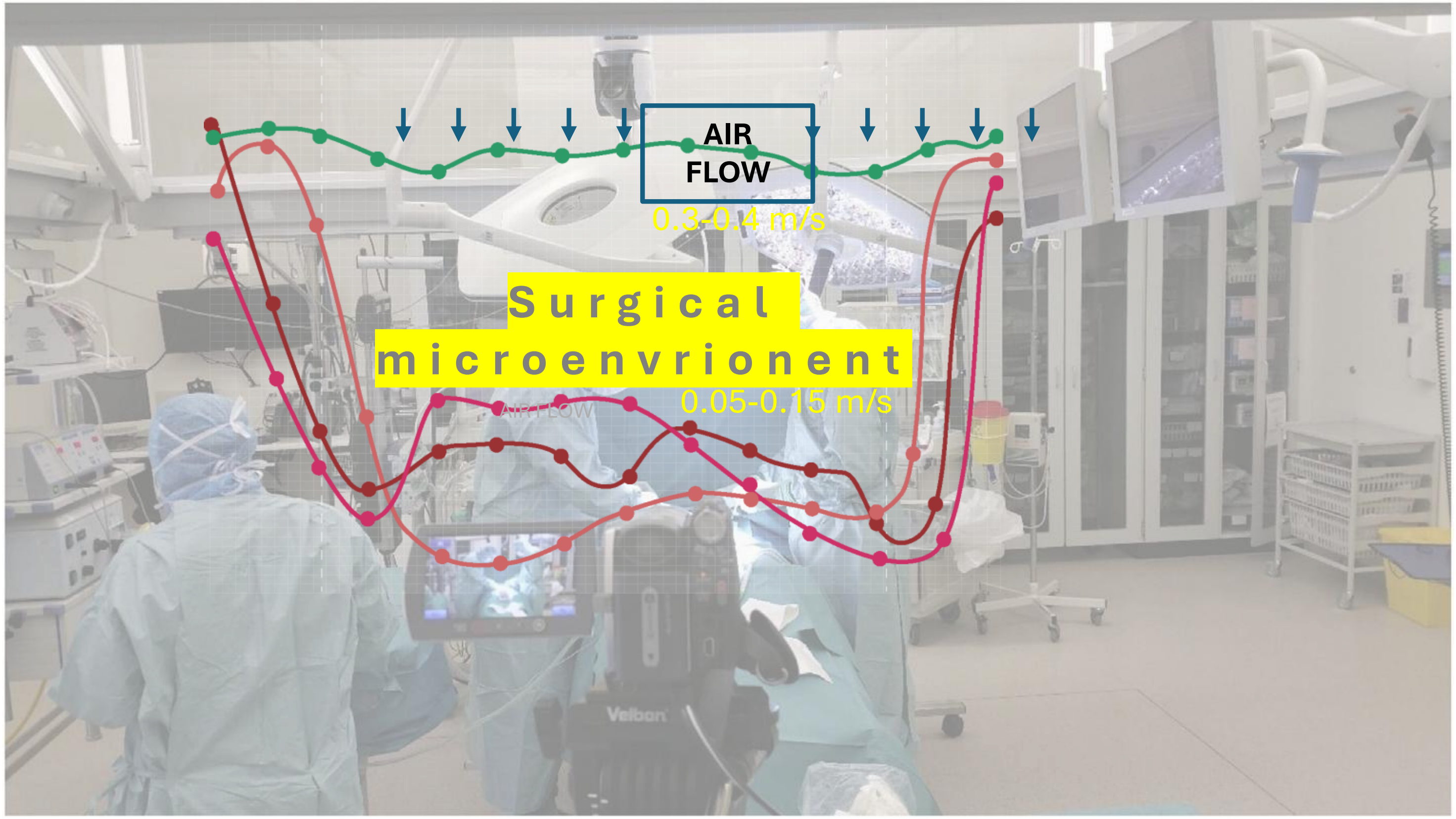
How surgical facilities affect laminar airflow?



- Measured airflow velocity distribution in an OR with laminar airflow at St. Olavs hospital

Disturbance of surgical lamp on clean air distribution

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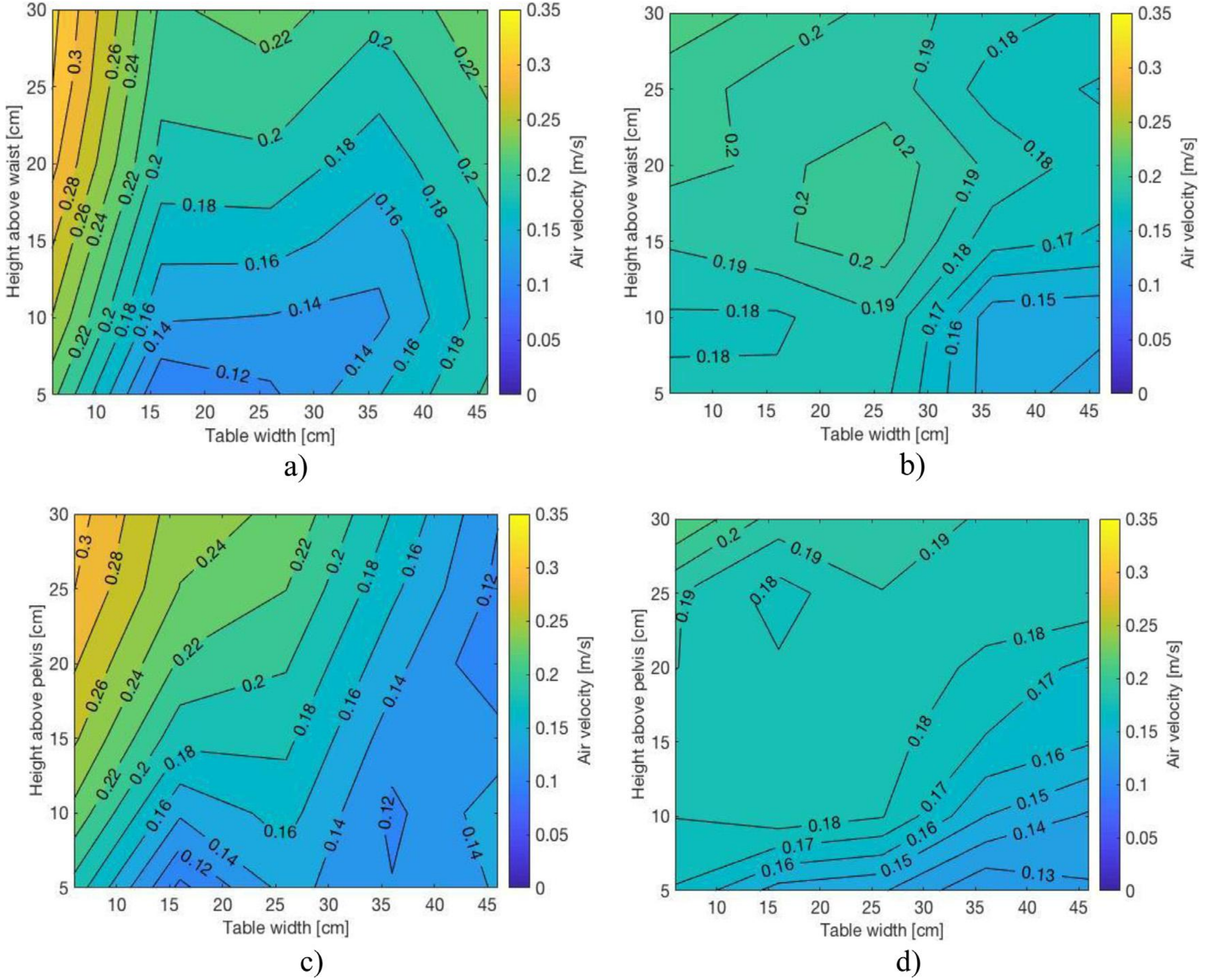
Velocity distribution over a simulated patient



Velocity contours above a lying patient surrounded by 3 surgical staff (scenario 1), including cases 3 and 4. (a) Above-the-waist position with an LAF system, (b) above-the-waist position with an MV system, (c) above-the-pelvis position with an LAF system, and (d) above-the-pelvis position with an MV system.

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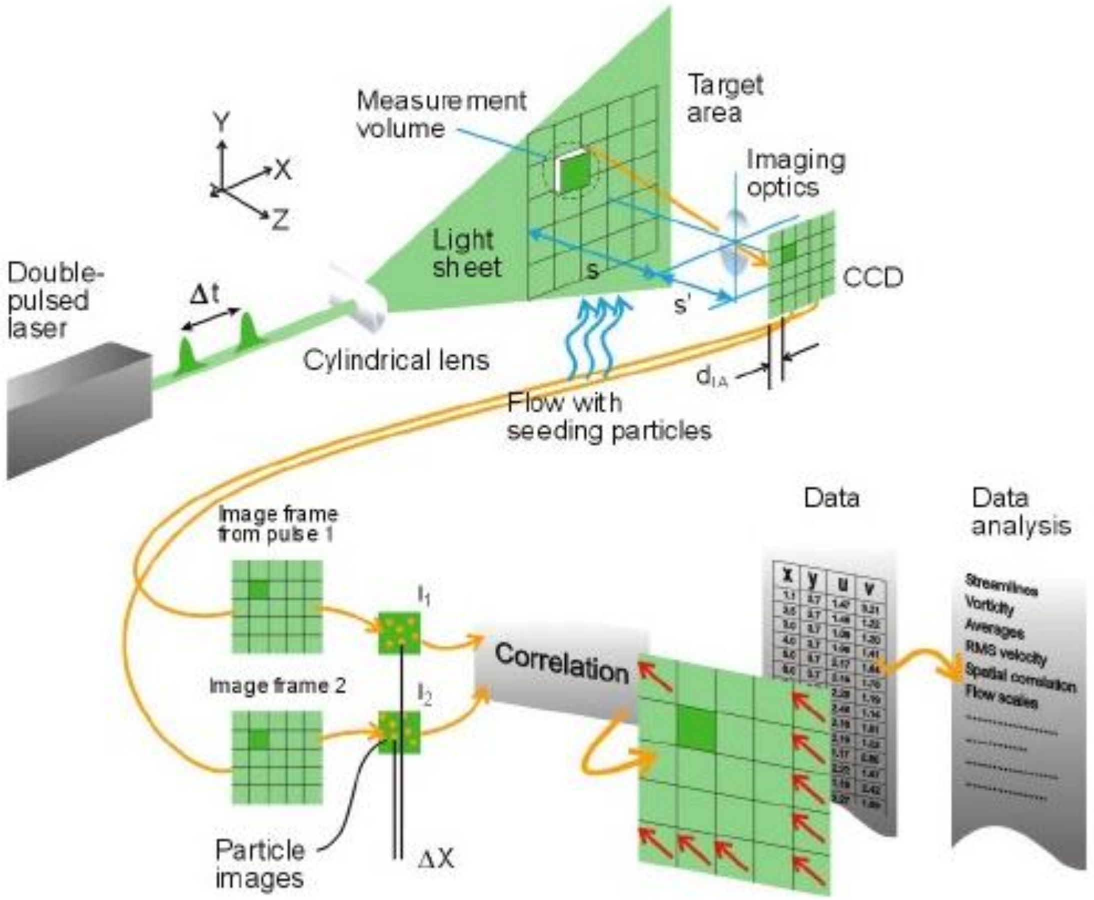
Introduction - Particle Image Velocimetry



What is PIV?

PIV stands for Particle Image Velocimetry

It is a non-intrusive, whole-flow-field optical technique used for fluid velocity measurement

It involves tracking the movement of small tracer particles illuminated by a laser sheet and captured using high-speed cameras.

1. Guide. "Oxford Instruments." *Oxford Instruments*, 2016, andor.oxinst.com/learning/view/article/piv-mode-for-istar-scmos. Accessed 7 Feb. 2025.
2. "High-Speed 3D Velocimetry System." *Www.buffalo.edu*, www.buffalo.edu/shared-facilities-equip/facilities-equipment/velocimetry-system.html.
3. "Measurement Principles of PIV - Dantec Dynamics." *Dantec Dynamics | Precision Measurement Systems & Sensors*, www.dantecdynamics.com/solutions/fluid-mechanics/particle-image-velocimetry-piv/measurement-principles-of-piv/.
4. Raffel, Markus, et al. *Particle Image Velocimetry*. *Springer EBooks*, Springer Nature, 1 Jan. 2007. Accessed 24 Apr. 2023.

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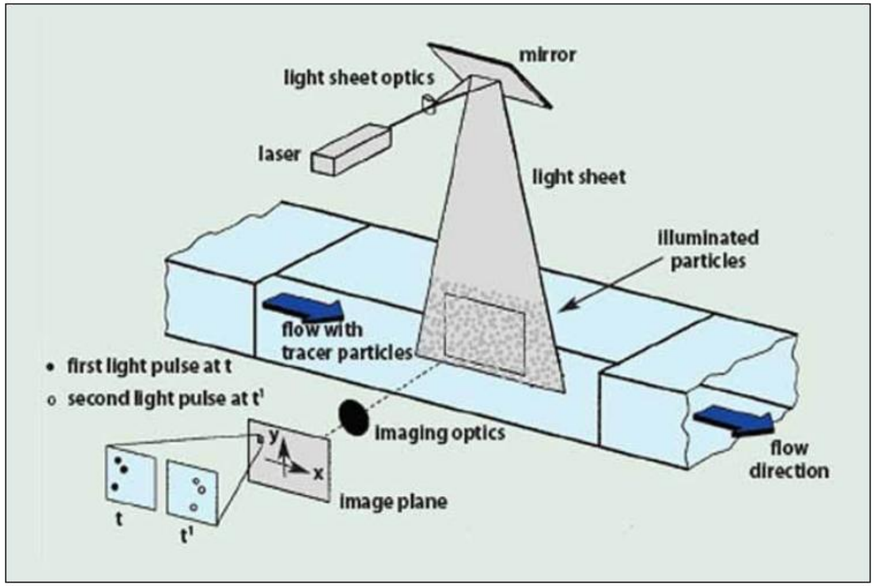
Basic Principles of PIV and Experimental Setup of PIV

How it works?

- Add tracer particles to the flow
- Illuminate particles in a plane with two laser pulses
- Record scattered light from particles
- Analyze particle displacement between pulses
- Calculate velocity vectors
- $u = \frac{\Delta x}{\Delta t}, v = \frac{\Delta y}{\Delta t}$

Experimental Setup



Key components:

- Tracer particle seeding system
- Light source: Laser and light sheet optics
- High-quality imaging system (camera and lens)
- Synchronization system
- Data acquisition and processing system

1. M. Kelnberger, InnoLas GmbH; G. Schwitzgebel, Universität Mainz. "Particle Image Velocimetry: Basics, Developments and Techniques." *Photonics.com*, Photonics Media, 13 Apr. 2006, www.photonics.com/Articles/Particle_Image_Velocimetry_Basics_Developments/a2512

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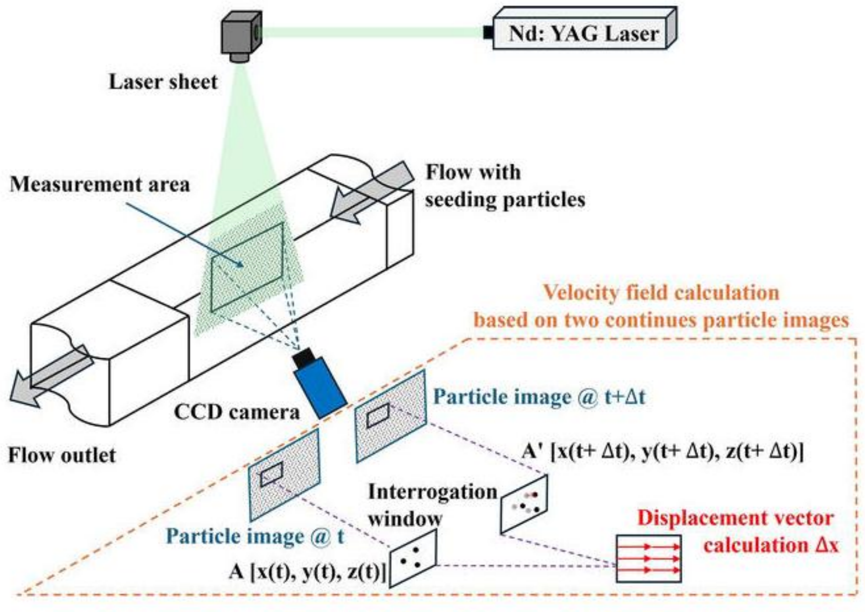
Specific Features of PIV

1. **Non-intrusive velocity measurement technique** (in contrast to probe-using techniques such as pressure tubes and hot wire anemometers)
   - Optical technique, no probes required
   - Suitable for low/high-speed flows and boundary layers
2. **Indirect velocity measurement**
   - Measuring the velocity of a fluid element indirectly by the means of measuring of the velocity of tracer particles within the flow
3. **Whole field technique**
   - Records large parts of flow fields simultaneously
   - High spatial resolution(enabling the detection of wide range of spatial structures even in unsteady flow fields), limited temporal resolution



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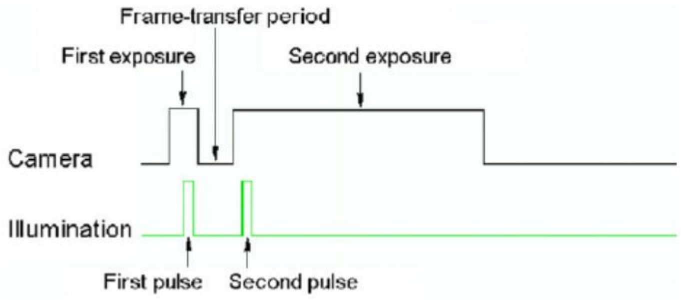
Technical Considerations

1. **Particle selection**
   - Small enough to follow flow f(Velocity lag/Small particles follow the flow better)
   - Large enough for adequate light scattering
2. **Illumination**
   - High-power light source for gas flows
   - Lower power acceptable for liquid flows
3. **Timing of illumination pulses**
   - The duration of the illumination light pulse must be short enough to “freeze” the motion of the particles to avoid image blurring.
   - Optimal time delay between pulses for accurate displacement measurement



**The need to utilize larger particles because of their better light scattering efficiency is in contradiction to the demand to have as small particles as possible in order to follow the flow faithfully. In most applications a compromise has to be found.

1. “Nanotoxicology: Particle Selection - NanoComposix.” *NanoComposix*, 2016, nanocomposix.com/pages/nanotoxicology-particle-selection. Accessed 7 Feb. 2025.
2. Thielicke, William. “Low-Cost Particle Image Velocimetry Setup: Pulsed Laser Diode for PIV Illumination.” *Blogspot.com*, Blogger, 23 Nov. 2021, pivlab.blogspot.com/2021/11/pulsed-laser-diodes-for-piv.html. Accessed 7 Feb. 2025.

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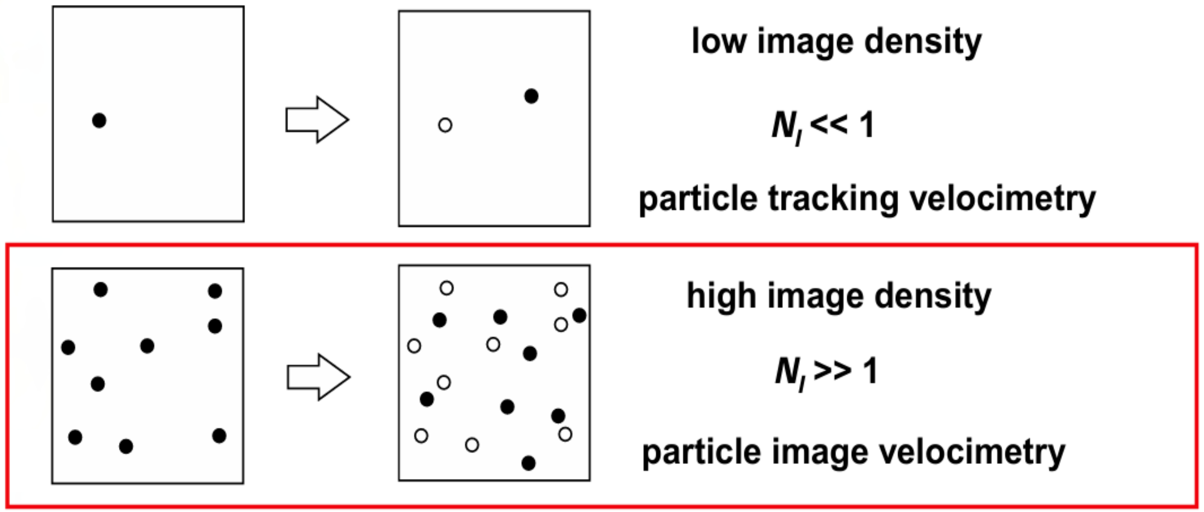
Image Capturing and Processing

1. **Particle image density**
   - Low: Particle Tracking Velocimetry (PTV)
   - Medium: Standard PIV
   - High: Laser Speckle Velocimetry (LSV)

2. **Recording methods**
   - Single frame vs. multiple frame capture 2C-PIV (two components) vs. 3C-PIV (three components)



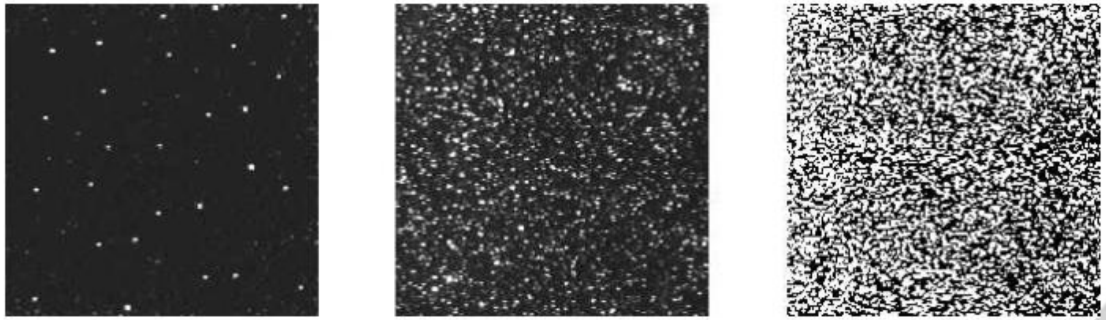


Fig. 1.5. The three modes of particle image density: (a) low (PTV), (b) medium (PIV), and (c) high image density (LSV).

1. "Magnetism." *Questions and Answers in MRI*, mriquestions.com/cine-parameters.html.
2. Raffel, Markus, et al. *Particle Image Velocimetry*. *Springer EBooks*, Springer Nature, 1 Jan. 2007. Accessed 24 Apr. 2023.
3. Etminan, Amin & Muzychka, Yuri & Pope, Kevin & Nyantekyi-Kwakye, Baafour. (2022). Flow visualization: state-of-the-art development of micro-particle image velocimetry. Measurement Science and Technology. 33. 10.1088/1361-6501/ac75b0

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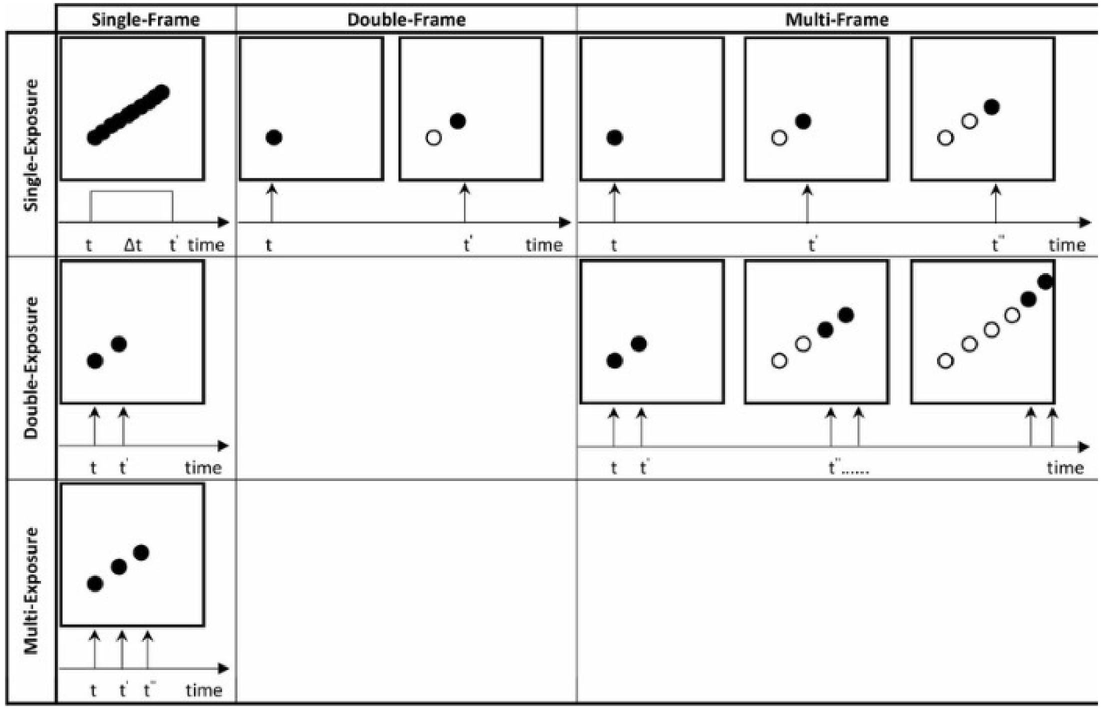
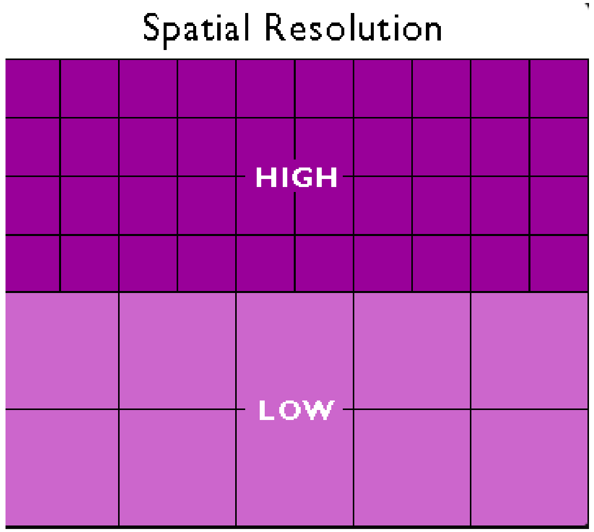
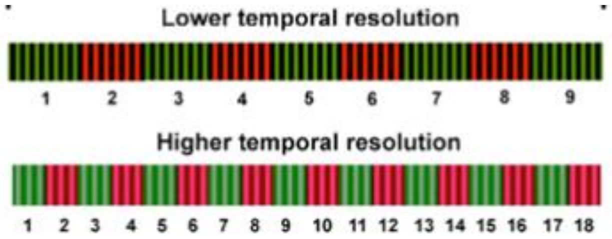
Image Capturing and Processing

3. Spatial and temporal resolution

- **High spatial resolution** (The size of the interrogation areas must be small enough for the velocity gradients not to have significant influence on the results)
- **Improving temporal resolution with high-speed lasers and cameras**







1. "Magnetism." *Questions and Answers in MRI*, mriquestions.com/cine-parameters.html.
2. Raffel, Markus, et al. *Particle Image Velocimetry*. *Springer EBooks*, Springer Nature, 1 Jan. 2007. Accessed 24 Apr. 2023.
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Physical and Technical Background of Particle Image Velocimetry (PIV)

Tracer particles/Particle Behavior in Fluid

- Equation:

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

$$\mathbf{U}_p(t) = \mathbf{U}\left[1 - \exp\left(-\frac{t}{\tau_s}\right)\right]$$

- U_s Velocity Lag
- U Fluid's Velocity
- U_p Particle's Velocity

*Assumption: spherical particles(with density much greater than the fluid's density) in a viscous fluid at a very low Reynolds number /the fluid acceleration is constant and Stokes drag does apply

- Relaxation time:
  - a convenient measure to evaluate the tendency of particles to attain velocity equilibrium with the fluid.

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

- Factors affecting particle motion
  - Particle size
  - Density
  - Fluid viscosity

1. Raffel, Markus, et al. *Particle Image Velocimetry*. *Springer EBooks*, Springer Nature, 1 Jan. 2007. Accessed 24 Apr. 2023.

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Physical and Technical Background

Relation to PIV: Stokes number

$$\mathrm{St} = \frac{\tau_s}{\tau_f}$$

- τ_s = particle relaxation time
- τ_f = fluid time scale

$$\tau_f \approx \frac{L}{U}$$

- where:
- L= characteristic length scale of the flow (m)
- U= characteristic velocity of the flow (m/s)

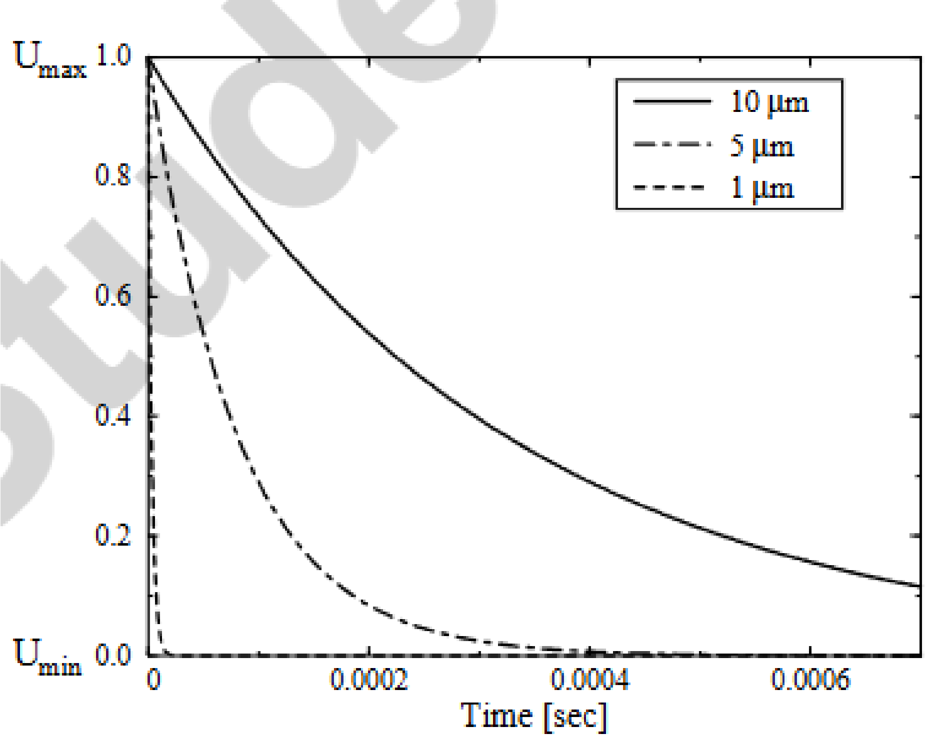

Fig. 2.1. Time response of oil particles with different diameters in a decelerating air flow.

Interpretation:

•**St ≪ 1** → particles follow the flow well (good PIV tracers)

•**St ≈ 1 or larger** → particles lag (measurement error)

1. Raffel, Markus, et al. *Particle Image Velocimetry*. *Springer EBooks*, Springer Nature, 1 Jan. 2007. Accessed 24 Apr. 2023.

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Physical and Technical Background

Examples in indoor airflow / ventilation

- Particle diameter: $d_p = 1\ \mu m$
- Air kinematic viscosity: $\nu \approx 1.5 \times 10^{-5}\ \mathrm{m^2/s}$

$$\tau_s \approx \frac{(10^{-6})^2}{1.5 \times 10^{-5}} \approx 6.7 \times 10^{-8}\ \mathrm{s}$$

Room airflow

- $U \sim 0.1\ m/s$
- $L \sim 0.1–1\ m$

$$\tau_f \sim \frac{0.1–1}{0.1} = 1–10\ \mathrm{s}$$

$$\mathrm{St} = \frac{\tau_s}{\tau_f}$$

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$$\tau_s \approx \frac{(10^{-6})^2}{1.5 \times 10^{-5}} \approx 6.7 \times 10^{-8}\ \mathrm{s}$$

Near a supply diffuser (high shear)

$$U \sim 1\ m/s$$
$$L \sim 0.01\text{–}0.05\ m$$

$$\tau_f \sim 0.01\text{–}0.05\ \mathrm{s}$$

$$\mathrm{St} = \frac{\tau_s}{\tau_f}$$

Interpretation:

•**St ≪ 1** → particles follow the flow well (good PIV tracers)

•**St ≈ 1 or larger** → particles lag (measurement error)

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Discussions

- What kind of fluid time scale in your project?
- Whether PIV may be a suitable method in your reserach?

- τ_s = particle relaxation time
- τ_f = fluid time scale

$$\mathrm{St} = \frac{\tau_s}{\tau_f}$$

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Seeding particles in Particle Image Velocimetry (PIV)

Particle Generation and Supply

Seeding materials

- For Liquids: Polystyrene, hollow glass spheres, aluminum flakes

Table 2.1. Seeding materials for liquid flows.

Type	Material	Mean diameter in μm
Solid	Polystyrene	10 – 100
	Aluminum flakes	2 – 7
	Hollow glass spheres	10 – 100
	Granules for synthetic coatings	10 – 500
Liquid	Different oils	50 – 500
Gaseous	Oxygen bubbles	50 – 1000

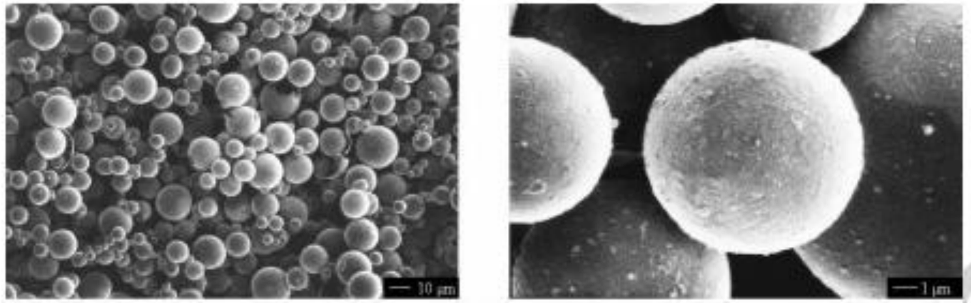
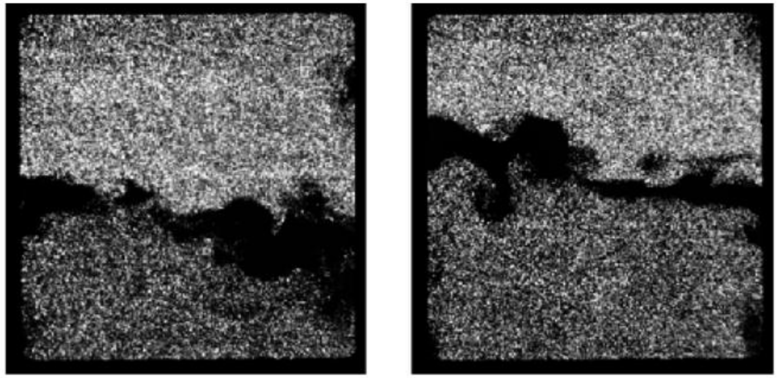


Fig. 2.8. Micrographs of silver coated hollow glass spheres: ×500 and ×5000.

- For Gases: Polystyrene, titanium dioxide, oil droplets

Table 2.2. Seeding materials for gas flows.

Type	Material	Mean diameter in μm
Solid	Polystyrene	0.5 – 10
	Alumina Al_2O_3	0.2 – 5
	Titania TiO_2	0.1 – 5
	Glass micro-spheres	0.2 – 3
	Glass micro-balloons	30 – 100
	Granules for synthetic coatings	10 – 50
	Dioctylphathalate	1 – 10
	Smoke	< 1
Liquid	Different oils	0.5 – 10
	Di-ethyl-hexyl-sebacate (DEHS)	0.5 – 1.5
	Helium-filled soap bubbles	1000 – 3000



PIV raw images of oil droplets showing evidence of local extinction/ reignition, with droplets penetrating the dark high-temperature region.

1. Raffel, Markus, et al. *Particle Image Velocimetry*. *Springer EBooks*, Springer Nature, 1 Jan. 2007. Accessed 24 Apr. 2023.

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Challenges in Gas Flow Seeding

- **Velocity Lag:**
  - Density difference between the gaseous bulk fluid and particles can cause significant velocity lag
- **Health Concerns:**

  Experimentalists may inhale seeded air
- **Particle Handling:**
  - Liquid droplets evaporate quickly
  - Solid particles are difficult to disperse and tend to agglomerate
- **Injection Complexities:**
  - Particles must be injected into the flow shortly before the gaseous medium enters the test section.
  - The injection must not disturb the flow
  - Homogeneous distribution is crucial
- **Insufficient Mixing:**
  - Exciting Turbulence in most experimental sertups often not strong enough to mix particles adequately
  - Requires multiple injection points (Distributors, like rakes consisting of many small pipes with a large number of tiny holes, are often used.)
- **Particle Requirements:**
  - Must be suitable for transport in small pipes

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Generation and Supplying Particles Techniques for Seeding Gas Flows

- Fluidized beds: Used for dispersing dry powders into gas flows
- Condensation generators: Produce aerosols by evaporating liquids and then precipitating them
- Atomizers: Generate liquid droplets or disperse solid particles suspended in evaporating liquids
- Laskin nozzle generators: Commonly used for producing oil droplets in air flows for PIV measurements

1. "Laskin Aero X: Aerosol Generators | TCR Tecora." *TCR TECORA® - Official Website*, 8 July 2021, tcr-tecora.com/en/laboratory-instruments/laskin-aero-x-aerosol-generators/. Accessed 7 Feb. 2025.

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Oil Droplet Seeding System

- Laskin nozzle generator

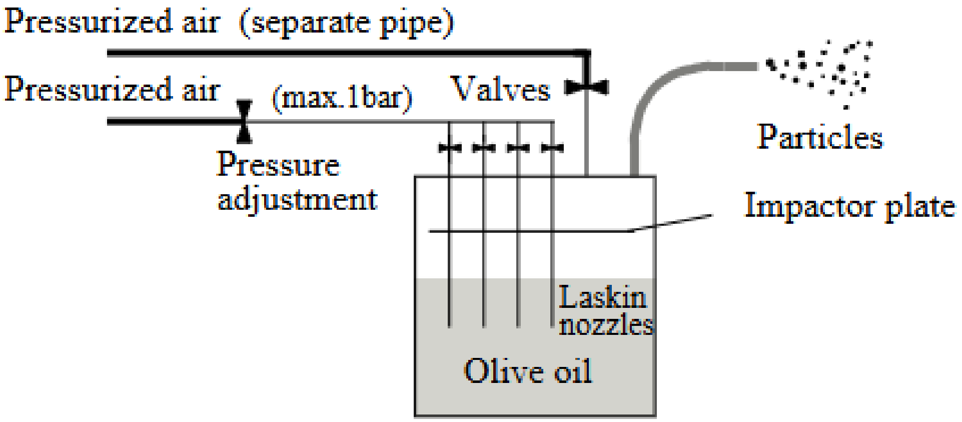

Fig. 2.9. Oil seeding generator.

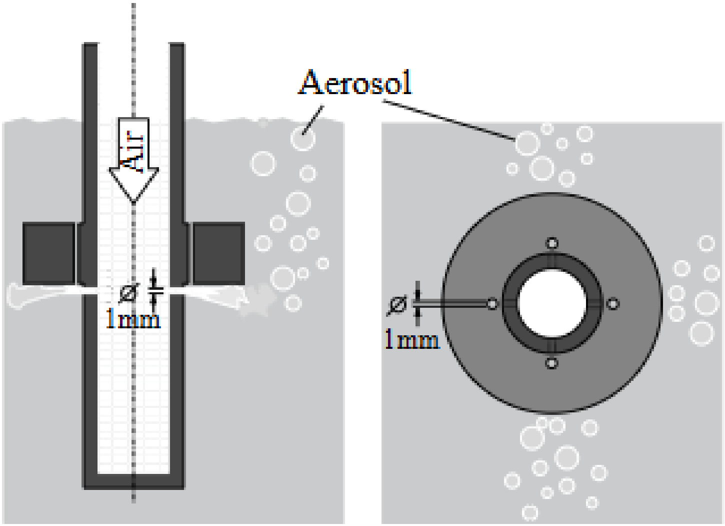

Fig. 2.10. Sketch of a Laskin nozzle.

1. Raffel, Markus, et al. *Particle Image Velocimetry*. *Springer EBooks*, Springer Nature, 1 Jan. 2007. Accessed 24 Apr. 2023.

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Fluidized Bed Seeding Device

- **Key features:**
  - Vertical tube with powder aerated from below
  - Sonic orifice at exit breaks up agglomerates
  - Switchable by-pass line maintains constant mass flow

- **Fluidized Bed Consideration for Optimal Performance**
  - Keep powder dry (heat before use if necessary)
  - Use dry air or nitrogen
  - Use short supply lines
  - Add carrier air to reduce seeding concentration
  - Frequently agitate the system
  - Consider adding small brass spheres (two-phase fluidized bed)

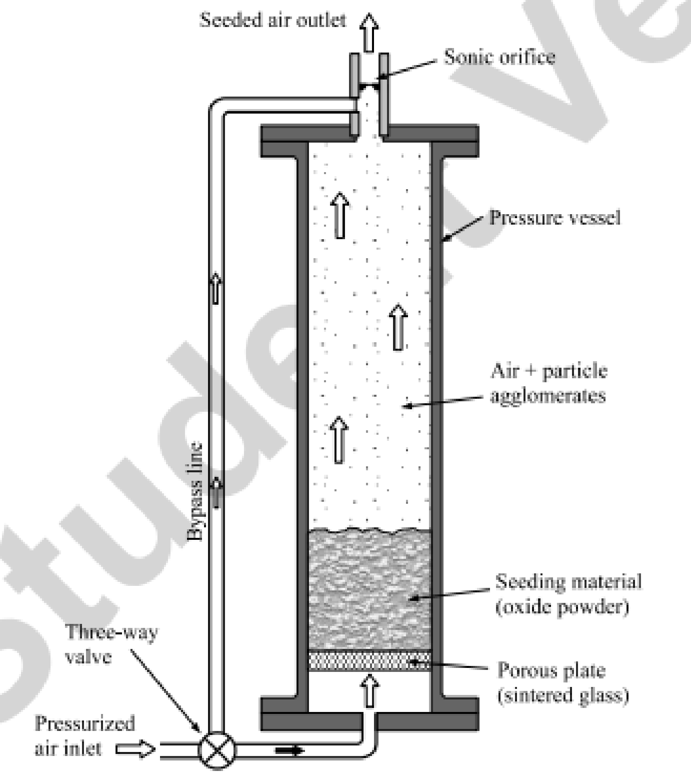

Fig. 2.14. Fluidized bed seeding device for high pressure applications

1. Raffel, Markus, et al. *Particle Image Velocimetry*. *Springer EBooks*, Springer Nature, 1 Jan. 2007. Accessed 24 Apr. 2023.

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Soap bubble seeding for air flows

- The finite scattering efficiency of any tracer particle is usually the limiting factor when increasing the field of view (FOV) in an actual PIV measurement.
- A well established method to provide neutrally buoyant particles with dimensions around 1–3 mm is the generation of helium-filled soap bubbles, where a helium filling of the particles compensates for their gravity.

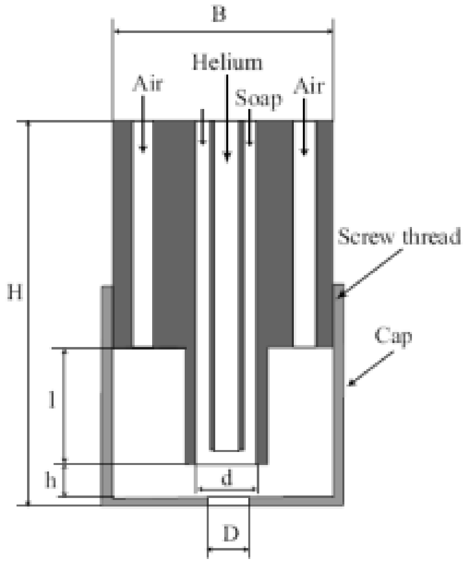

Fig. 2.13. Schematic drawing of an orifice type nozzle for the generation of He-filled soap bubbles [63].

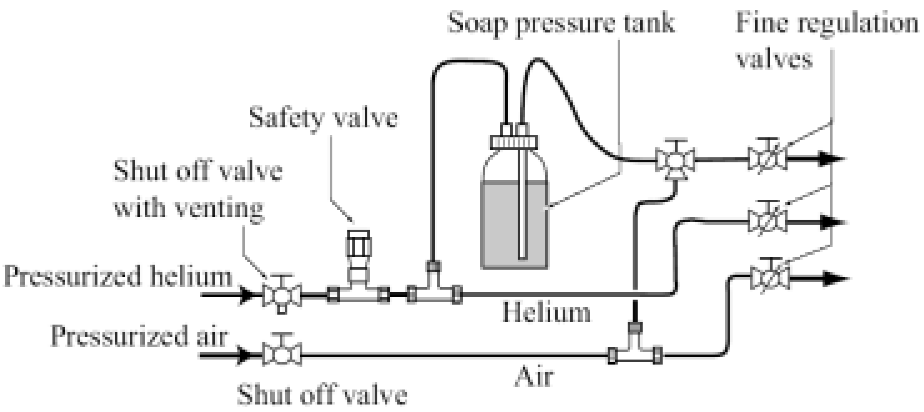

Fig. 2.15. Scheme of the air, helium and soap supply for a bubble generator [63].

1. Raffel, Markus, et al. *Particle Image Velocimetry*. *Springer EBooks*, Springer Nature, 1 Jan. 2007. Accessed 24 Apr. 2023.

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Light Sources in Particle Image Velocimetry (PIV)

Light Sources in Particle Image Velocimetry (PIV)

- Lasers are the primary light source in PIV due to their:
  - Monochromatic light.
  - High energy density.
  - Ability to form thin light sheets for illuminating and recording the tracer particles without chromatic aberrations.

- Laser Components:
  - Laser Material: Gas, semiconductor, or solid.
  - Pump Source: Excites laser material.
  - Mirror Arrangement (Resonator): Amplifies light.

- Principles of Laser Operation:

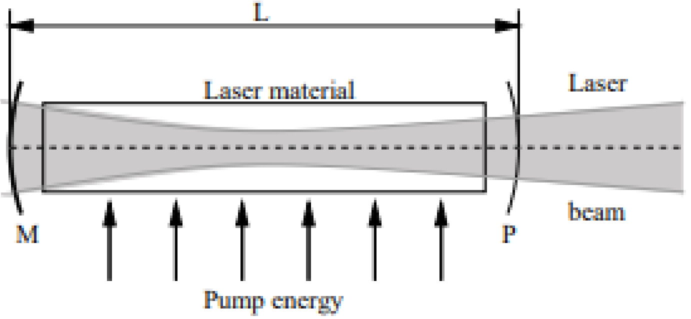

Fig. 2.16. Schematic diagram of a laser

1 Quantum Mechanics
2 Interaction with electromagnetic radiation
3 Energy level diagram

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Types of Commonly Used Lasers in PIV

- Commonly used lasers for PIV *(Semiconductor lasers):*
  - Nd:YAG lasers(532 nm)/(yttrium-aluminum-garnet) : High pulse energy, commonly used for air-based PIV.
  - Nd:YLF lasers (527 nm)/(yttrium lithium fluoride) : Suitable for time-resolved measurements.

PIV lasers are mostly designed as double oscillator systems. This enables the user to adjust the separation time between the two illuminations of the tracer particles independently of the pulse strength.

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Light Sheet Intensity Profiles at Different Distances

- A good beam profile is absolutely essential for PIV.
- It must be specified not only in the near and in the far field – as most manufacturers do – but also in the mid-field at a distance of 2–10 m from the laser.

- Fig 2.20 shows the intensity profiles of a light sheet measured at four distances from the laser: 1.8 m, 3.3 m, 4.3 m, and 5.8 m.
  - The thickness of the light sheet increases with distance from the laser.
  - A small side peak is visible at all positions except at 5.8 m, where it disappears.
  - At position 4.3 m, fluctuations in the intensity distribution are minimized, making it an optimal distance for uniform illumination.

- **Important Note:**
  - The loss of correlation in PIV recordings is influenced by the intensity distribution of the light sheet at the recording plane.

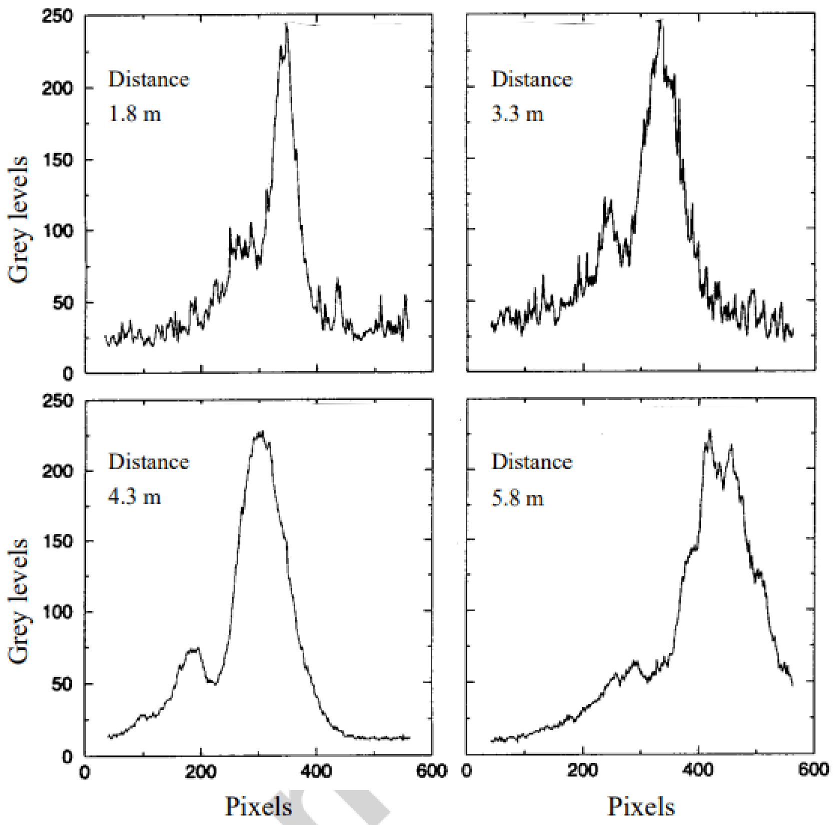

Fig. 2.20. Evolution of the light sheet profile with increasing distance from the laser.

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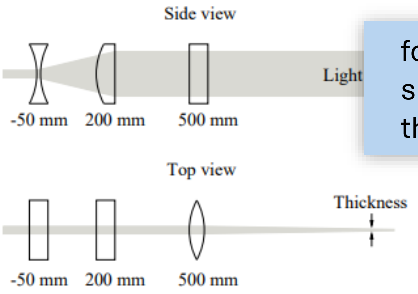
Light Sheet Optics for PIV

- **Aim:**

Light sheet optics create a thin, uniform light sheet to illuminate particles in PIV experiments.

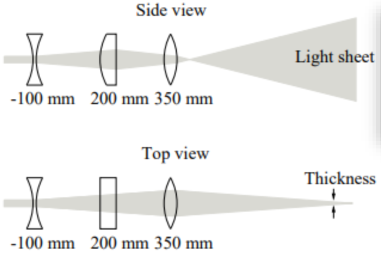
- **Lens Configurations:**
  - Cylindrical lenses are essential for generating light sheets.
  - Combinations of cylindrical and spherical lenses improve versatility and control over sheet height and thickness.

- **Challenges:**
  - The critical region close to the focal line must be covered to avoid reflections caused by dust or seeding particles, which could lead to beam distortion or damage.
  - Reflections and aberrations must be minimized for optimal beam properties.



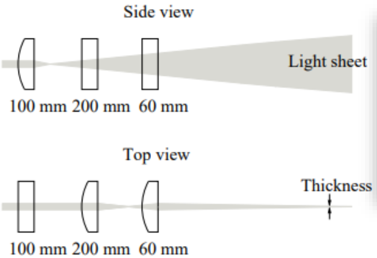
for constant light sheet height and thickness.

Fig. 2.26. Light sheet optics using three cylindrical lenses (one of them with negative focal length).



for adaptable light sheet geometry.

Fig. 2.27. Light sheet optics using two spherical lenses (one of them with negative focal length) and one cylindrical lens.



for thin, consistent light sheets with high energy per unit area.

Fig. 2.28. Light sheet optics using three cylindrical lenses.

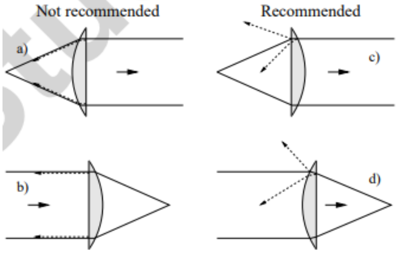


Fig. 2.29. General considerations on the orientation of lenses inside the light sheet optics.

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PIV Image Recording
in Particle Image Velocimetry (PIV)

PIV recording techniques

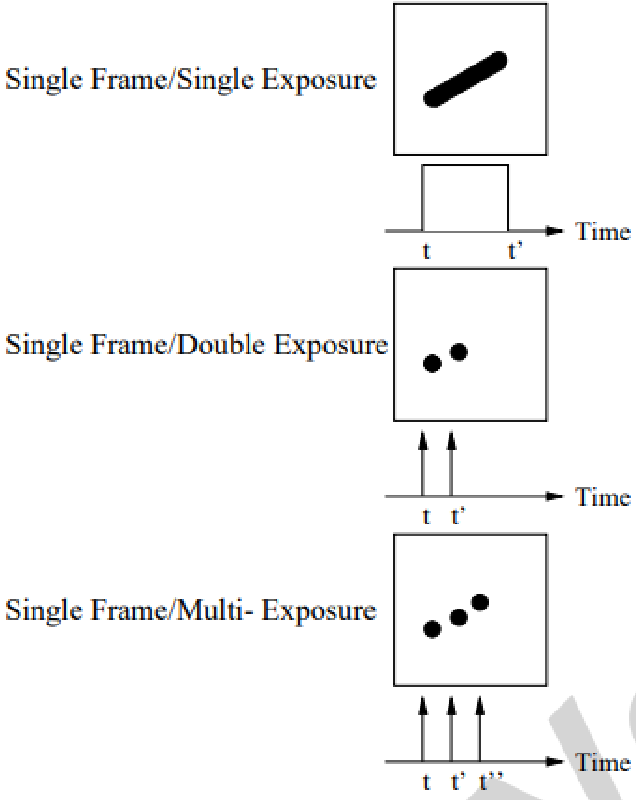

Fig. 4.1. Single frame techniques.

Two Main Categories:

- Single frame/multi-exposure PIV
- Multi-frame/single exposure PIV

Single Frame/Multi-Exposure PIV:

- Captures illuminated flow on a single frame
- Lacks temporal order information
- Requires additional techniques to resolve directional ambiguity:
  - Displacement biasing
  - Image shifting (rotating mirror or birefringent crystal)
  - Pulse tagging
  - Color coding

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PIV recording techniques

Multi-Frame/Single Exposure PIV:

- Provides single illuminated image per illumination pulse
- Preserves temporal order of particle images
- Preferred method when technologically feasible
- Easier to evaluate

Experimental Setup Priorities/Considerations:

- Spatial/temporal resolution of flow field
- Resolution of velocity fluctuations
- Time interval between PIV measurements
- Available or affordable components

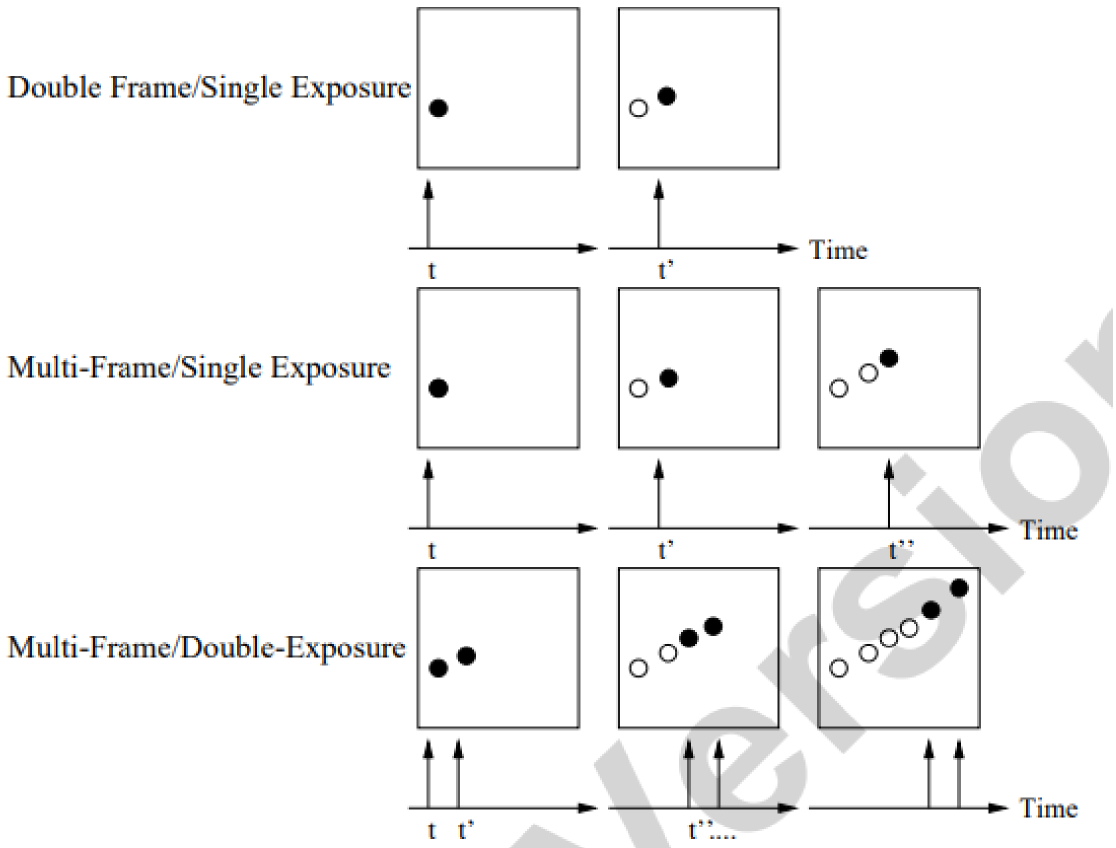

Fig. 4.2. Multiple frame techniques (open circles indicate the particles’ positions in previous frames).

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Nowadays Trends in PIV recordings techniques:

- Video recording preferred over photographic recording
- Advantages: Immediate feedback and quality optimization
- Consideration of operational costs

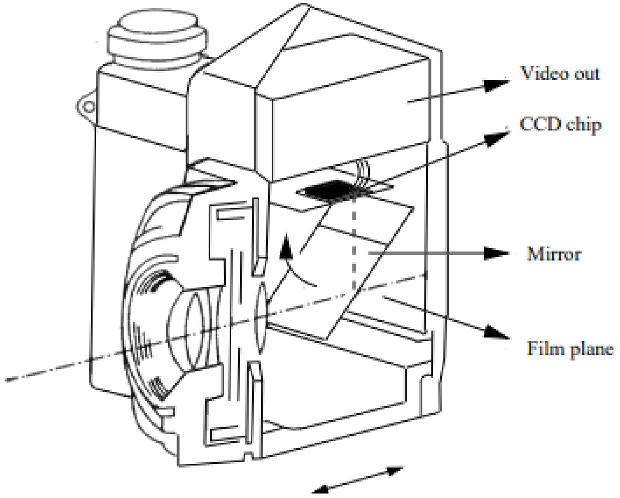

Fig. 4.3. Photo camera with CCD sensor for fast focusing.

Limitations in PIV recordings techniques:

- Technical constraints (laser power, pulse rates, camera frame rates)
- Not all requirements can be fulfilled simultaneously

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Film Cameras for PIV: Advantages and Challenges

Advantages:
- Higher spatial resolution compared to digital cameras
- Especially beneficial with large format films
- Can achieve resolutions over 10 times greater than digital
- Preferred for applications requiring high spatial resolution without peak-locking

Challenges:
- Difficulty recording tracer particles on different frames
- Problematic for high-speed investigations with microsecond pulse separations
- Requires solutions for directional ambiguity removal (e.g. image shifting)

Example PIV Film Camera Setup:
- High-quality, reliable focusing device is crucial
- Options for fast focusing:
    1. CCD camera observing film plane through camera back wall
    2. Low-cost CCD sensor in SLR viewfinder
- Precise alignment of CCD sensor distance to match lens-to-film plane distance
- Camera system on traversing table for adjusting light sheet to film plane distance
- Monitor used to observe and minimize particle image diameters

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High-Speed CCD Cameras

Specific Features:

- Designed for high-speed PIV applications requiring high spatial resolution.
- Frame rates of up to 1000 frames per second at moderate resolutions ($\sim 512 \times 512$ pixels).
- Incorporates split-frame storage:
  - Half of the image is read from the top, and the other half from the bottom.
  - Parallel readout reduces required readout speed.

Advantages:

- High frame rates enable capturing fast flow phenomena.
- Parallel readout minimizes bandwidth requirements and reduces noise.
- Suitable for applications requiring precise temporal resolution.

Challenges:

- Large data transfer demands require optimized electronics to reduce noise.
- Higher pixel readout rates increase complexity and cost.

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Single Frame/Multi-Exposure Recording

Challenge:

- Directional Ambiguity: When using photographic film or single-frame digital cameras, multiple exposures of the same particles are stored on a single recording.
- Problem: The direction of particle motion cannot be uniquely determined since the temporal order of illumination pulses is unknown.

Solutions:

- A Priori Knowledge: For flows with known direction, velocity vector signs can be inferred.
- Flow Reversal Scenarios: Techniques required for cases like separated flows where directional ambiguity must be resolved.

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Multi-Frame PIV Recording/Single-Exposure Recording

Advantages:

- Resolves directional ambiguity in velocity vectors.
- Allows flexible pulse separation times.
- Offers higher signal-to-noise ratios, enabling smaller interrogation windows and increased spatial resolution.

Illumination Coding Methods:

- **Polarization Coding:** Uses differently polarized light sheets but faces challenges like depolarization due to glass surfaces or larger particles.
- **Color Coding:** Employs color video cameras and color-coded light sheets; however, optical issues like focal plane displacement limit its applicability.

Timing-Based Separation:

- High-speed film cameras combined with copper vapor or Nd:YAG lasers.
- Suitable for specialized applications (e.g., piston engine flow studies).

Applications:

- Widely used in aerodynamic studies and flow investigations requiring precise velocity measurements.

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Cross-Correlation of a Pair of Two Singly Exposed Recordings

Principals

- Cross-correlates two frames of single exposures
- Assumes constant displacement D of particles

In the remainder of this section, a constant displacement $\mathbf{D}$ of all particles inside the interrogation volume is assumed, so that the particle locations during the second exposure at time $t' = t + \Delta t$ are given by:

$$\mathbf{X_i}' = \mathbf{X_i} + \mathbf{D} = \begin{pmatrix} X_i + D_X \\ Y_i + D_Y \\ Z_i + D_Z \end{pmatrix} .$$

Furthermore, we assume that the particle image displacements are given by:

$$\mathbf{d} = \begin{pmatrix} M D_X \\ M D_Y \end{pmatrix}$$

Image Intensity Fields

- First exposure: $I(\mathbf{x}, \mathbf{\Gamma})$
- Second exposure: $I'(\mathbf{x}, \mathbf{\Gamma}) = \sum_{j=1}^{N} V_0{}'(\mathbf{X_j} + \mathbf{D})\, \tau(\mathbf{x} - \mathbf{x_j} - \mathbf{d})$
- d: particle image displacement vector

Cross-Correlation Function

$$R_{II}(\mathbf{s}, \mathbf{\Gamma}, \mathbf{D}) = \sum_{i \neq j} V_0(\mathbf{X_i})\, V_0(\mathbf{X_j} + \mathbf{D})\, R_\tau(\mathbf{x_i} - \mathbf{x_j} + \mathbf{s} - \mathbf{d}) + R_\tau(\mathbf{s} - \mathbf{d}) \sum_{i=1}^{N} V_0(\mathbf{X_i})\, V_0(\mathbf{X_i} + \mathbf{D}) .$$

Components

$$R_{II}(\mathbf{s}, \mathbf{\Gamma}, \mathbf{D}) = R_C(\mathbf{s}, \mathbf{\Gamma}, \mathbf{D}) + R_F(\mathbf{s}, \mathbf{\Gamma}, \mathbf{D}) + R_D(\mathbf{s}, \mathbf{\Gamma}, \mathbf{D})$$

Convolution of mean intensities (R_C); Fluctuating noise component (R_F); Displacement correlation peak (R_D)

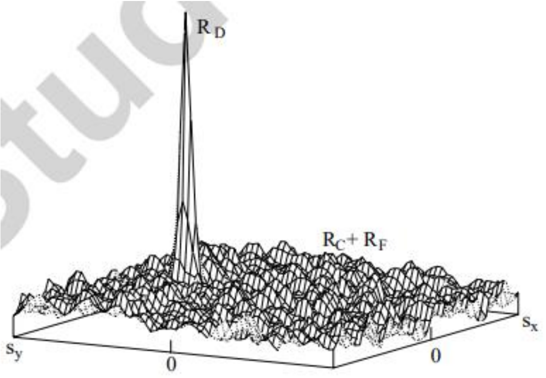

Fig. 3.6. Composition of peaks in the cross-correlation function.

Displacement Correlation Peak

$$R_D(\mathbf{s}, \mathbf{\Gamma}, \mathbf{D}) = R_\tau(\mathbf{s} - \mathbf{d}) \sum_{i=1}^{N} V_0(\mathbf{X_i})\, V_0(\mathbf{X_i} + \mathbf{D}) .$$

- Maximum at s = d
- Yields average in-plane displacement (U, V components)

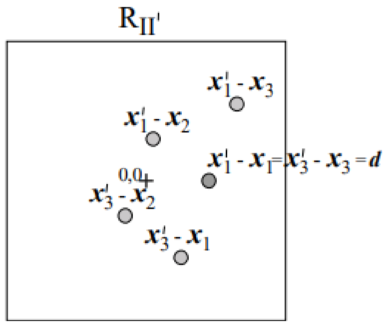

Fig. 3.7. Schematic representation of the cross-correlation of the intensity fields I and I' given in figure 3.5.

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Expected Value of Displacement Correlation

$$F_{\mathrm{I}}(D_X, D_Y) = \frac{\int\int W_0(X,Y)\, W_0(X+D_X, Y+D_Y)\, \mathrm{d}X\mathrm{d}Y}{\int\int W_0^2(X,Y)\, \mathrm{d}X\mathrm{d}Y} \qquad (3.10)$$

in-plane loss-of-pairs

$$F_{\mathrm{O}}(D_Z) = \frac{\int I_0(Z)\, I_0(Z+D_Z)\, \mathrm{d}Z}{\int I_0^2(Z)\, \mathrm{d}Z} . \qquad (3.11)$$

Out-of-plane loss-of-pairs

- When no in-plane or out-of-plane loss-of-pairs are present the two above Equs are unity.

$$E\{R_D(\mathbf{s}, \mathbf{D})\} = C_{\mathrm{R}}\, R_\tau(\mathbf{s} - \mathbf{d})\, F_{\mathrm{O}}(D_Z)\, F_{\mathrm{I}}(D_X, D_Y) \qquad (3.12)$$

where the constant C_{R} is defined as:

$$C_{\mathrm{R}} = \frac{N}{V_{\mathrm{F}}} \int_{V_{\mathrm{F}}} V_0^2(\mathbf{X})\, \mathrm{d}\mathbf{X} .$$

The expected value of the displacement correlation E{RD} for all realizations of Γ

Optimization of Correlation

$$|\mathbf{U}| = \frac{|\mathbf{d}(\Delta t)|}{M\,\Delta t} + \frac{\varepsilon_{\mathrm{resid}}}{M\,\Delta t} . \qquad (3.13)$$

Particle displacement; Residual error; Magnitude of measured velocity; Magnification; Pulse separation time

**The first parameter that has to be optimized during a PIV measurement is the pulse separation time between the successive light pulses. According to the principle of PIV the measured velocity is determined by the ratio of two components of the measured particle displacement between successive light pulses DX and DY respectively, and the pulse separation time Δt.

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Some case studies with
Particle Image Velocimetry (PIV)
Part I

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Introduction to PIV in Indoor Environments

The Challenge

Traditional anemometry provides only single-point measurements, making it difficult to capture instantaneous, whole-field turbulent structures in complex indoor air flows.

The Solution

Particle Image Velocimetry (PIV) offers a non-intrusive, high-resolution method to visualize and quantify complex air flow patterns in fractions of a second.

Research Focus

Investigating the entrainment process and turbulent behavior of attached plane jets discharged from active chilled beams in a full-scale room.

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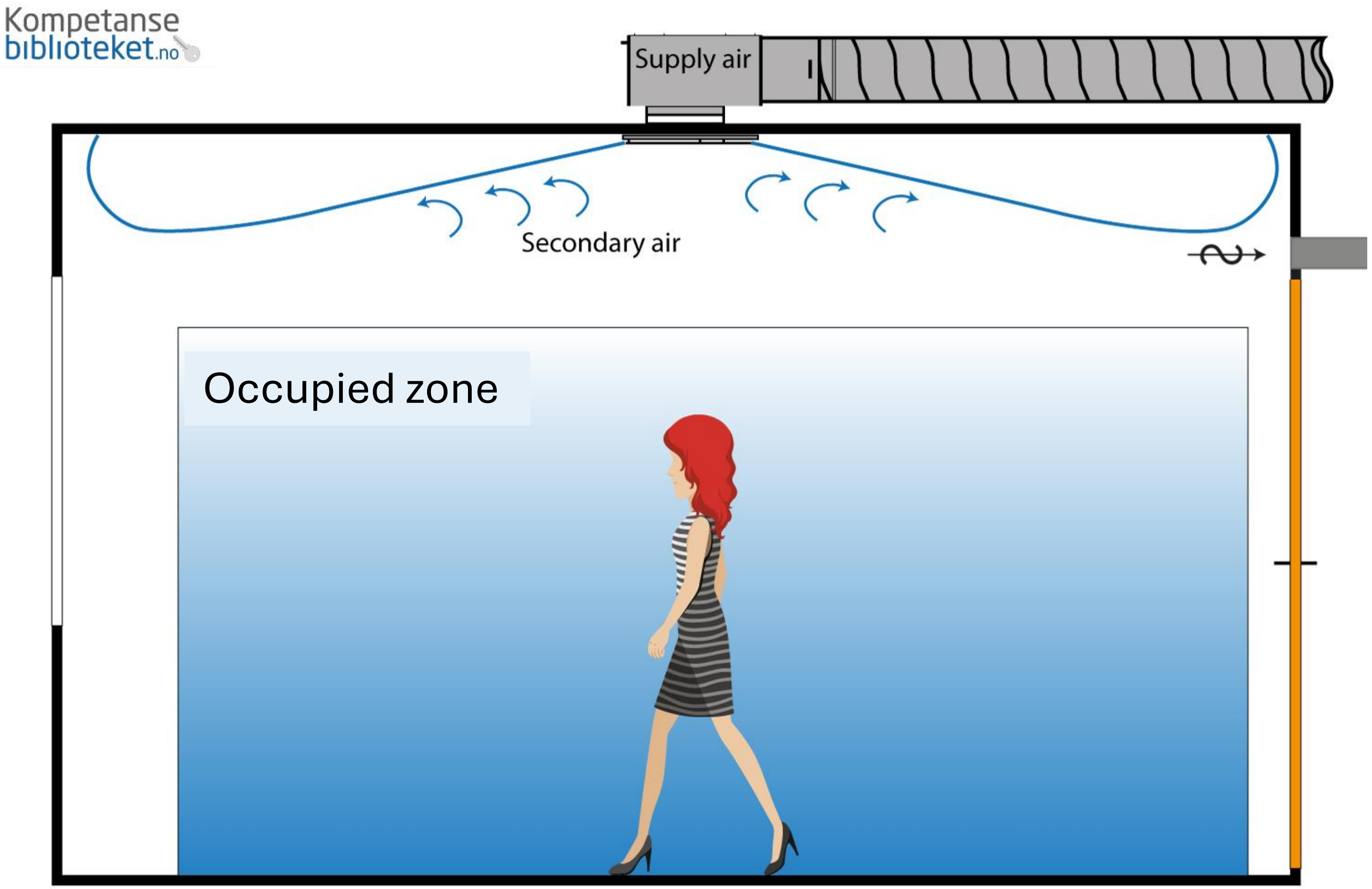
Case study: PIV Application in Indoor Air Distribution

Measurement of attached plane jets from active chilled beams in an office



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Case study: PIV Application in Indoor Air Distribution

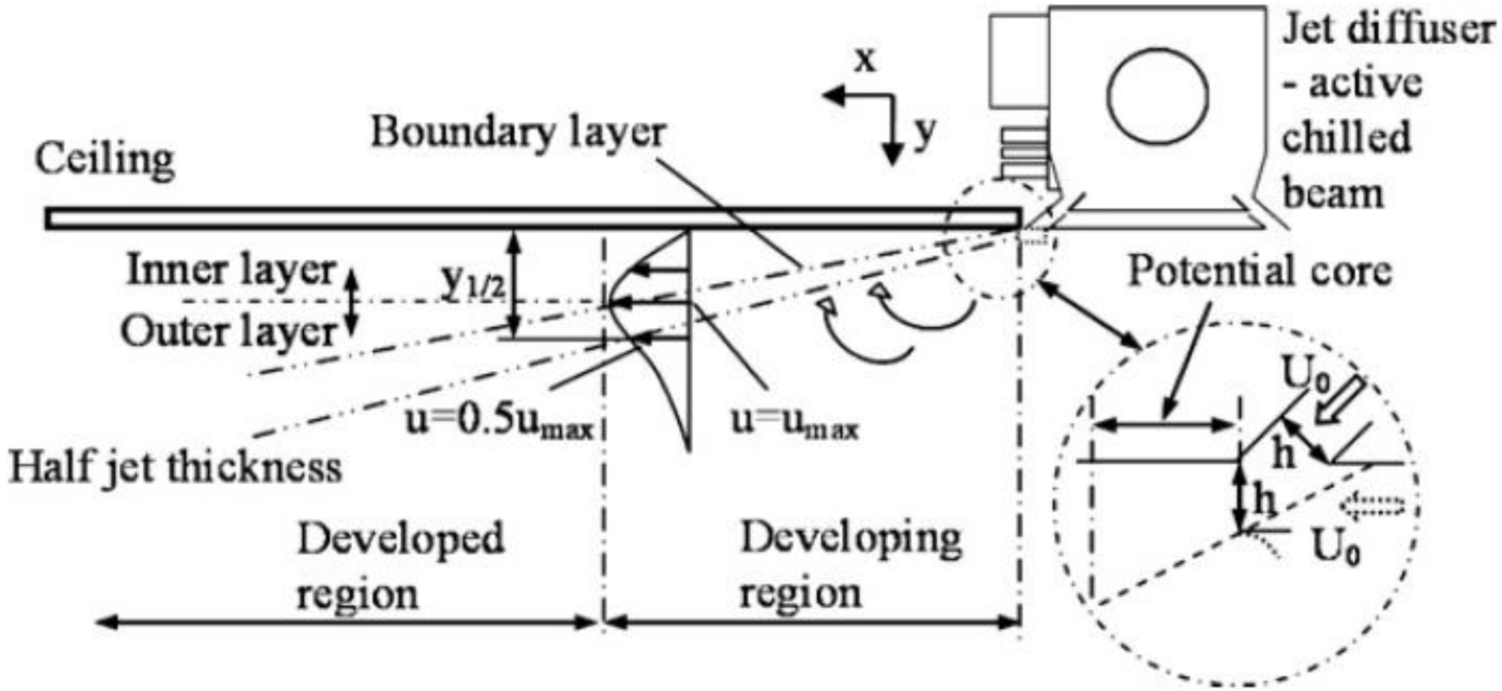

Fig. 1. Schematic view of the attached plane jet structure and jet regions in a room.

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The PIV Measurement System Architecture

Laser Source

Nd:YAG laser (200 mJ, 532 nm) generates a 1.0 mm thin light sheet to illuminate tracer particles in the flow field.

Imaging System

High-resolution CCD camera captures particle displacement between two laser pulses for velocity calculation.

Control & Timing

Programmable Timing Unit (PTU) synchronizes laser pulses and camera shutter with microsecond precision.

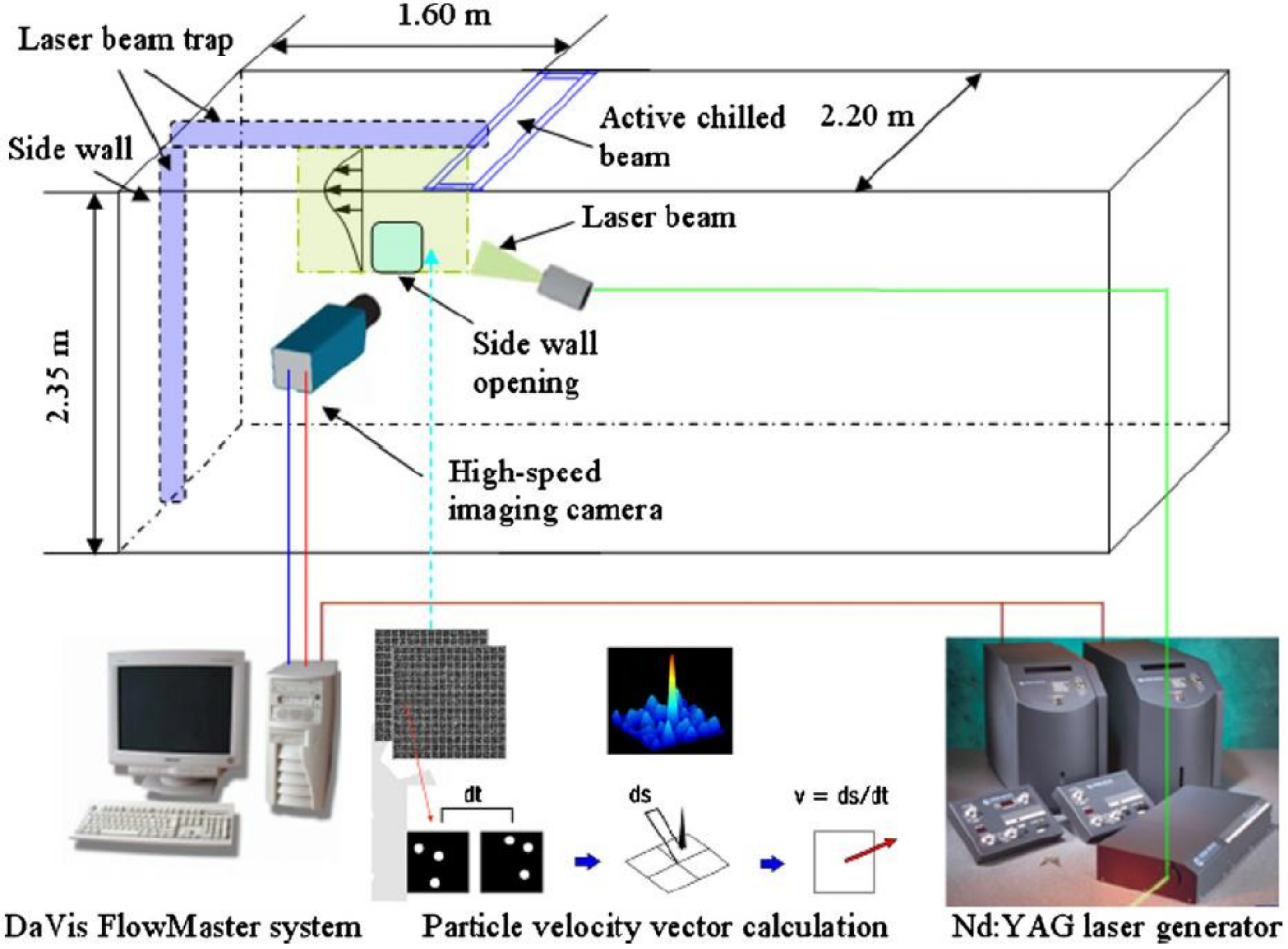

Fig. 3. Full-scale attached jet flow PIV measurement system.

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Systematic Measurement Procedure

01. Calibration

A large-scale calibration plate (800 mm x 800 mm) is used to ensure spatial accuracy across the entire measurement plane before data collection.

02. Flow Seeding

Tracer particles are introduced into the jet flow via a perforated plate, ensuring uniform distribution and optimal density for imaging.

03. Image Acquisition

Pairs of images are recorded at 10 Hz, with pulse intervals (dt) optimized for the expected flow velocities (3000–6000 μs).

04. Vector Calculation

Interrogation windows (64 x 64 pixels) with 75% overlap are processed using cross-correlation to resolve the velocity field.

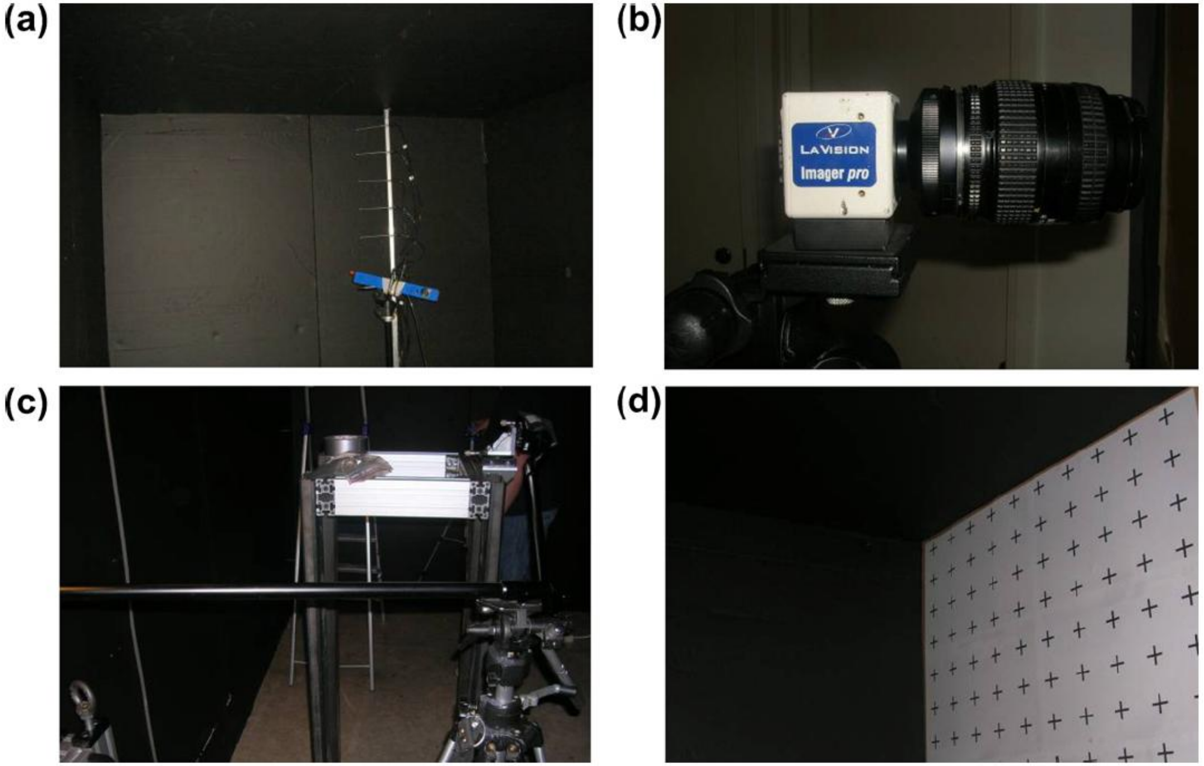

Fig. PIV measurement apparatus: (a) full-scale climate chamber with laser beam trap; (b) CCD camera; (c) laser guiding arm; (d) PIV measurement calibration plate.

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Experimental Setup and Conditions

Facility & Environment

Conducted in a full-scale climate chamber under strictly controlled isothermal conditions (23 ± 0.5 °C) to eliminate buoyancy effects.

Device Configuration

An active chilled beam was mounted flush to the ceiling, discharging an attached plane jet parallel to the longer wall.

Test Matrix: PIV Measurement Conditions

Case	Slot Velocity (m/s)	Reynolds Number	Turbulence Intensity
Case 1	0.8 ± 0.05	960	44%
Case 2	1.1 ± 0.05	1320	30%
Case 3	1.4 ± 0.05	1680	22%

** Slot height: 0.018 m. Sampling time: 8 s at 10 Hz recording speed.*

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Visualization of Turbulent Jet Structures

Flow Attachment

PIV visualization confirms that the jet attaches to the ceiling shortly after discharge due to the Coanda effect, restricting high-velocity air to the near-wall zone.

Vortex Dynamics

Large-scale vortices are clearly visible in the outer layer, driving the entrainment of ambient air and increasing the jet volume flow rate.

Turbulent Transition

Even at low Reynolds numbers (Re = 960), the jet exhibits fully turbulent behavior within a distance of 10 slot heights from the discharge.

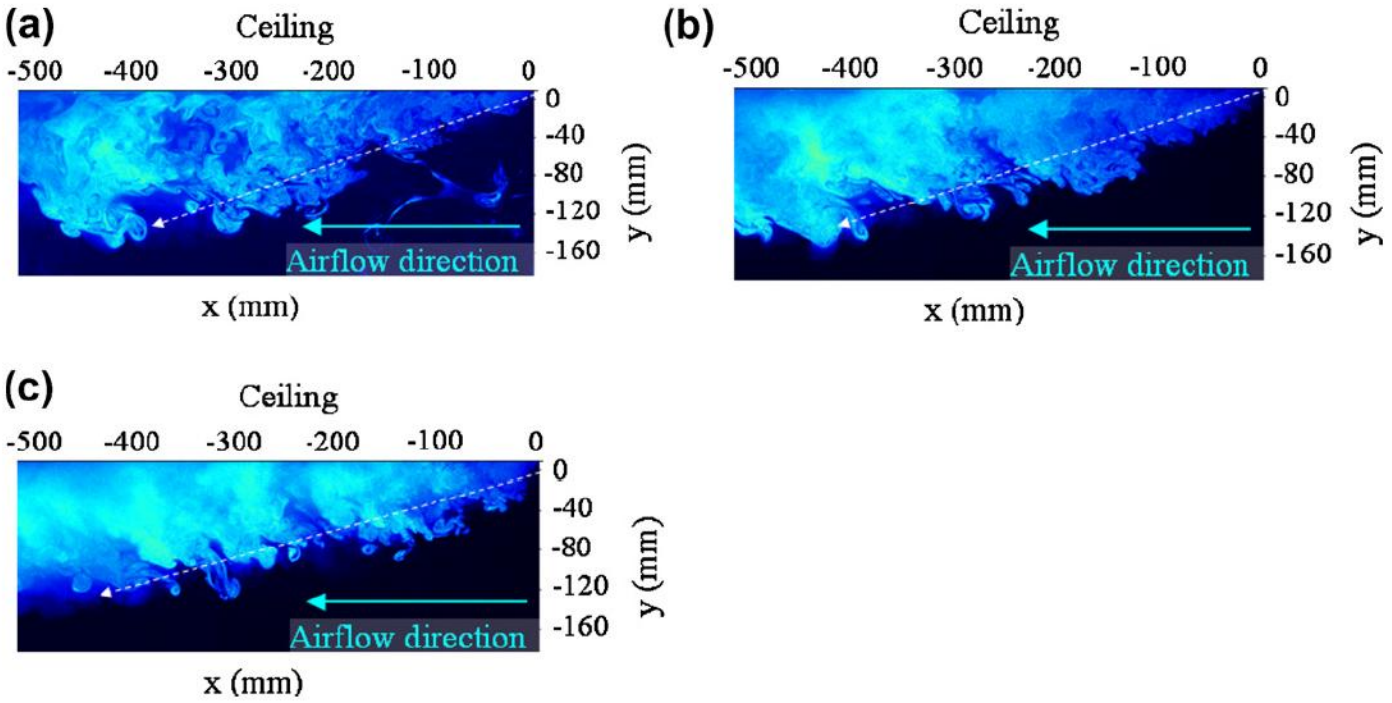

Fig. Photographs of the attached jet visualisation of the PIV image. (a) Case 1, slot velocity 0.8 m/s (Re = 960); (b) Case 2, slot velocity 1.1 m/s (Re = 1320); (c) Case 3, slot velocity 1.4 m/s (Re = 1680).

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Quantitative Velocity Field Analysis

Vector Fields

Averaged velocity maps reveal the spatial distribution of momentum. The jet remains attached to the ceiling across all tested Reynolds numbers.

Maximum Velocity

The highest velocities are consistently found near the ceiling surface, within the inner layer of the jet, confirming the wall-jet behavior.

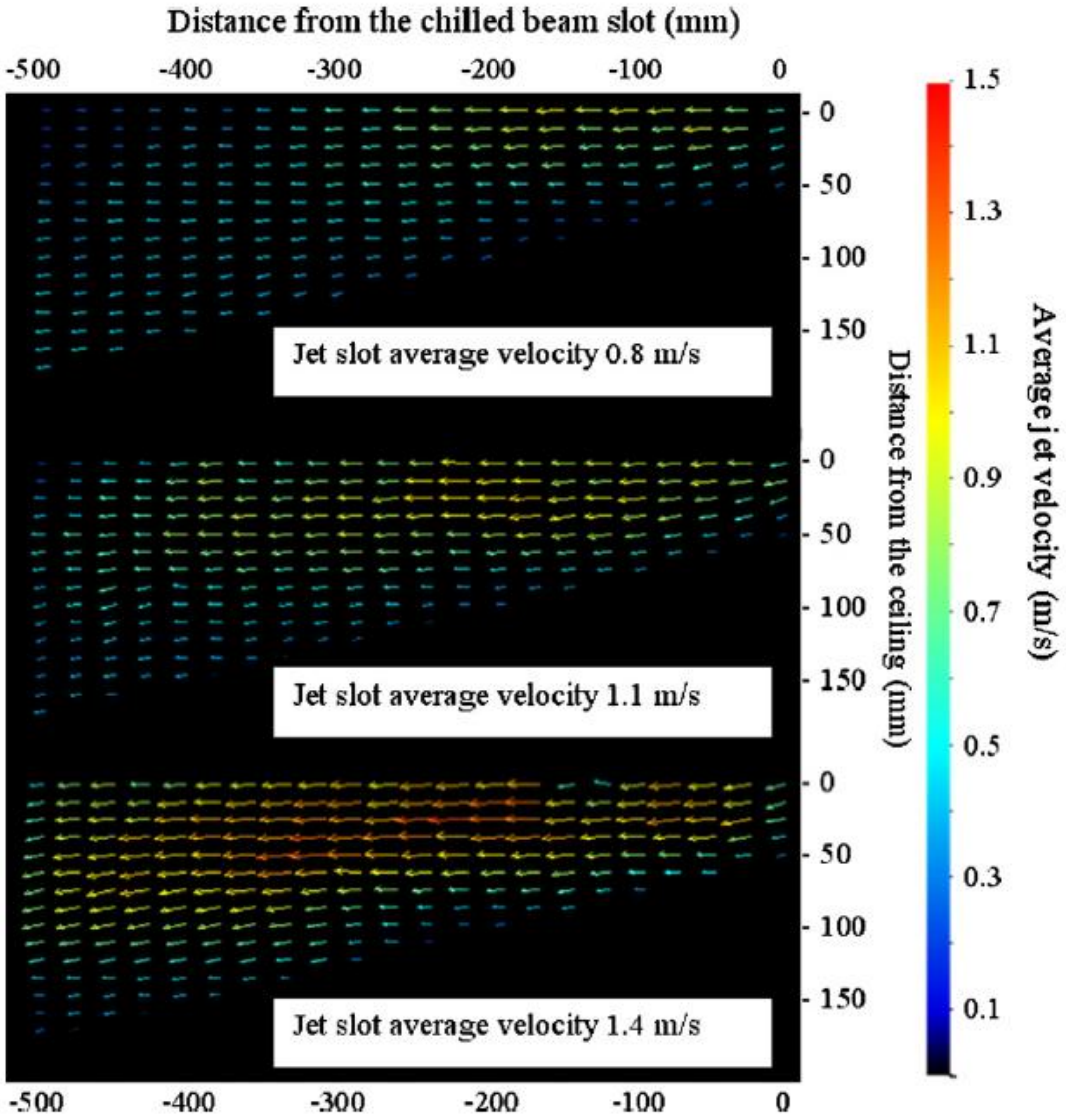

Fig . Jet velocity vector field distributions by PIV: a) slot velocity 0.8 m/s; b) 1.1 m/s; c) 1.4 m/s.

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Critical Challenges in Particle Seeding

The Seeding Compromise

Particles must be small enough to follow air streamlines (minimizing gravitational velocity) but large enough to reflect sufficient laser light for the CCD sensor.

Material Selection

Water droplets were found to adhere to duct surfaces, while OPTIMIST smoke provided a stable, non-disturbing seeding source with ideal light-scattering properties.

Concentration Control

Optimal seeding requires precise density. Low density reduces spatial resolution, while excess particles cause laser reflection and poor imaging performance.

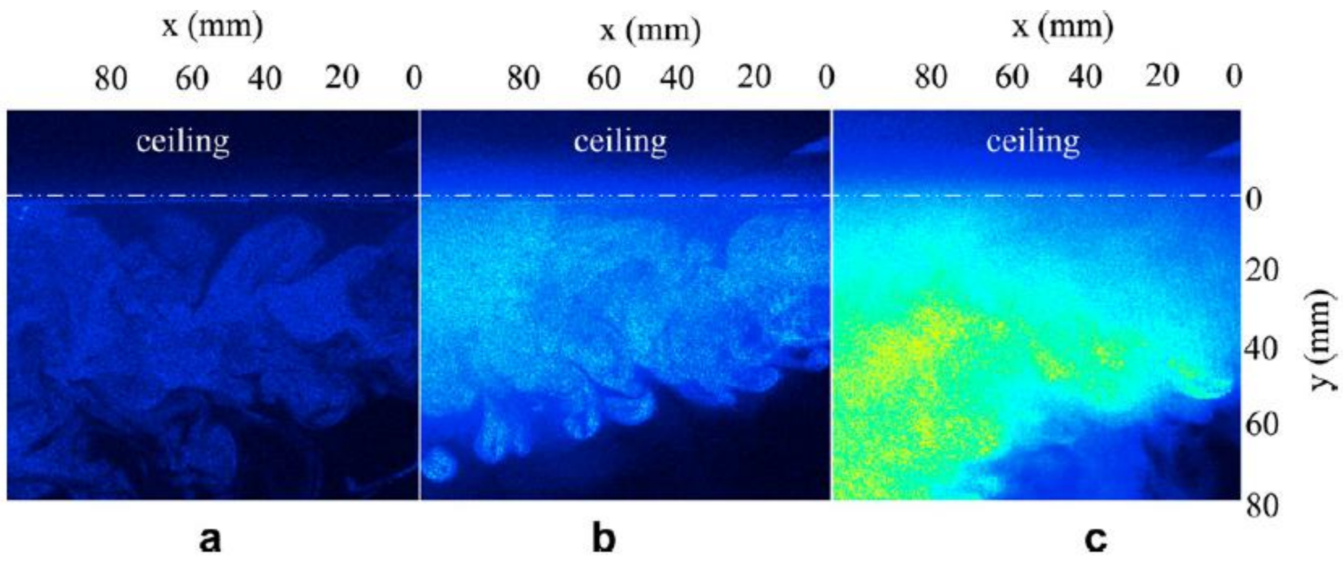

Fig. Photographs of jet flow with seeded particles: (a) insufficient particles; (b) acceptable seeding; (c) excess particles causing disturbance.

100 – 500
Optimal Intensity Counts

32 × 32 px
Interrogation Window

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Transient turbulent airflow

Comparative Analysis

PIV measurements were validated against traditional hot-sphere anemometer data at the jet slot and 300 mm downstream.

Reliability

The study demonstrates that PIV is a robust tool for validating CFD models and developing more accurate jet models for indoor air distribution design.

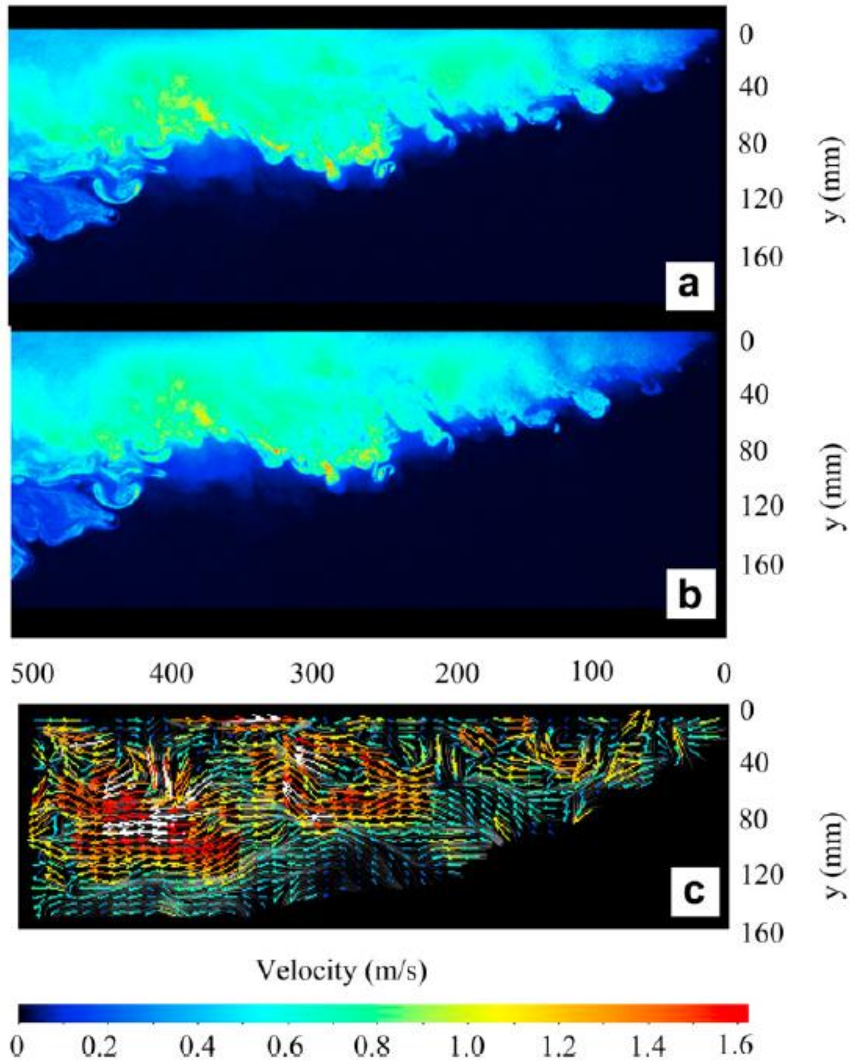

Fig. Jet visualisation and the corresponding instantaneous vector field by PIV pair photograph at a slot velocity of 1.4 m/s: a) laser sheet pair-image one; b) laser sheet pair-image two; c) instantaneous velocity vector field.

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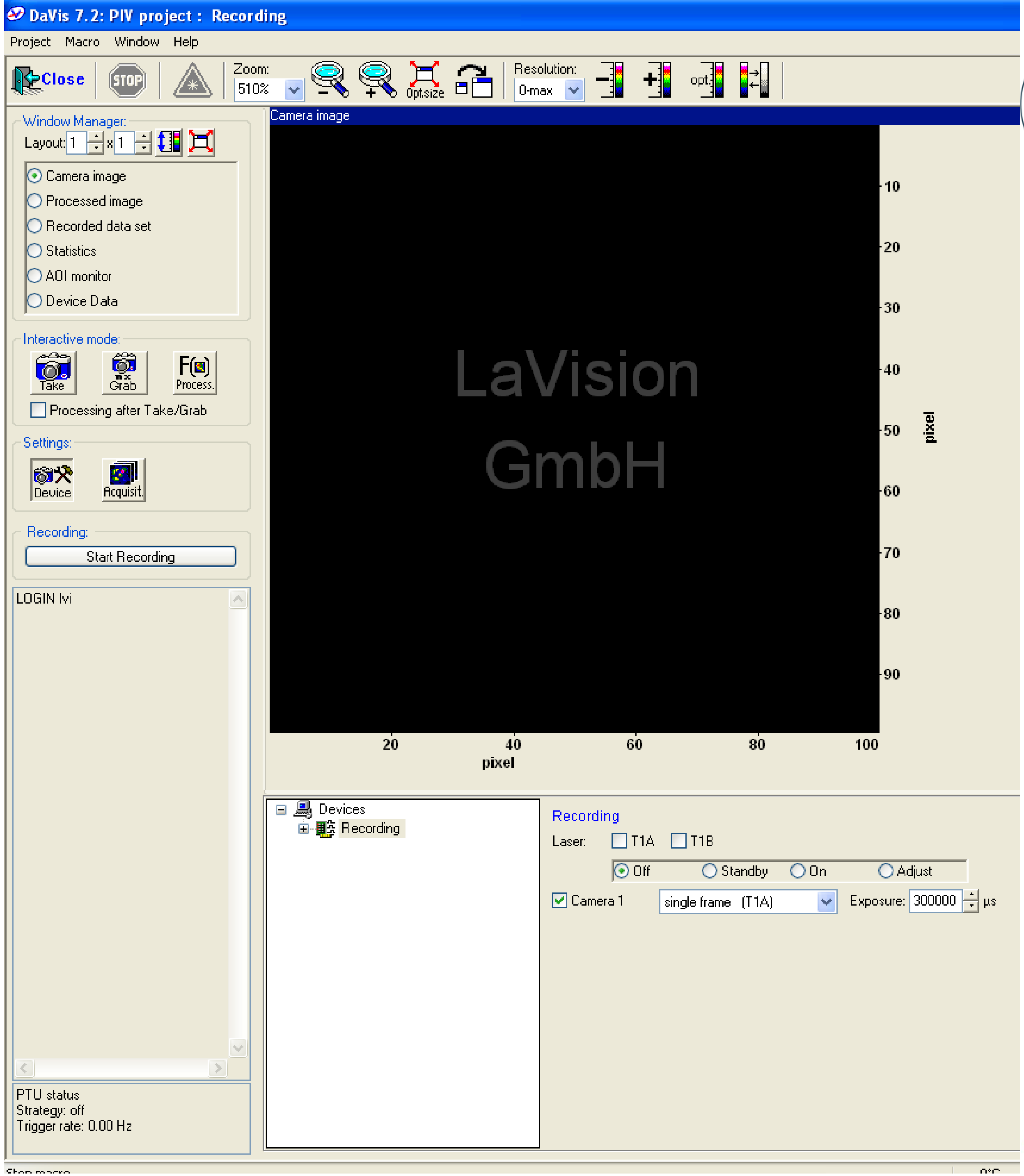
Lavision – DaVis PIV interface

Recording



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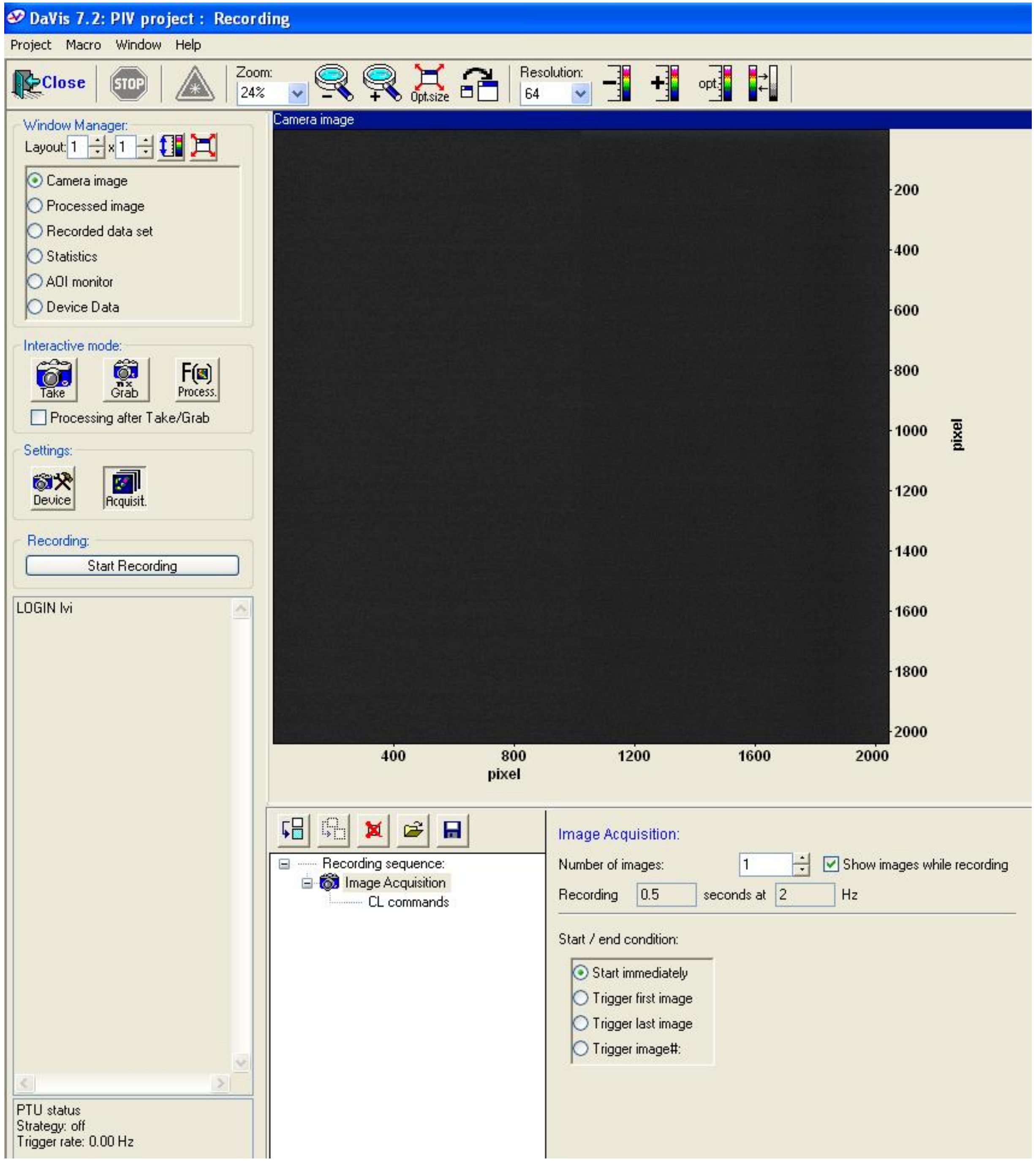
Lavision – DaVis PIV interface

Recording



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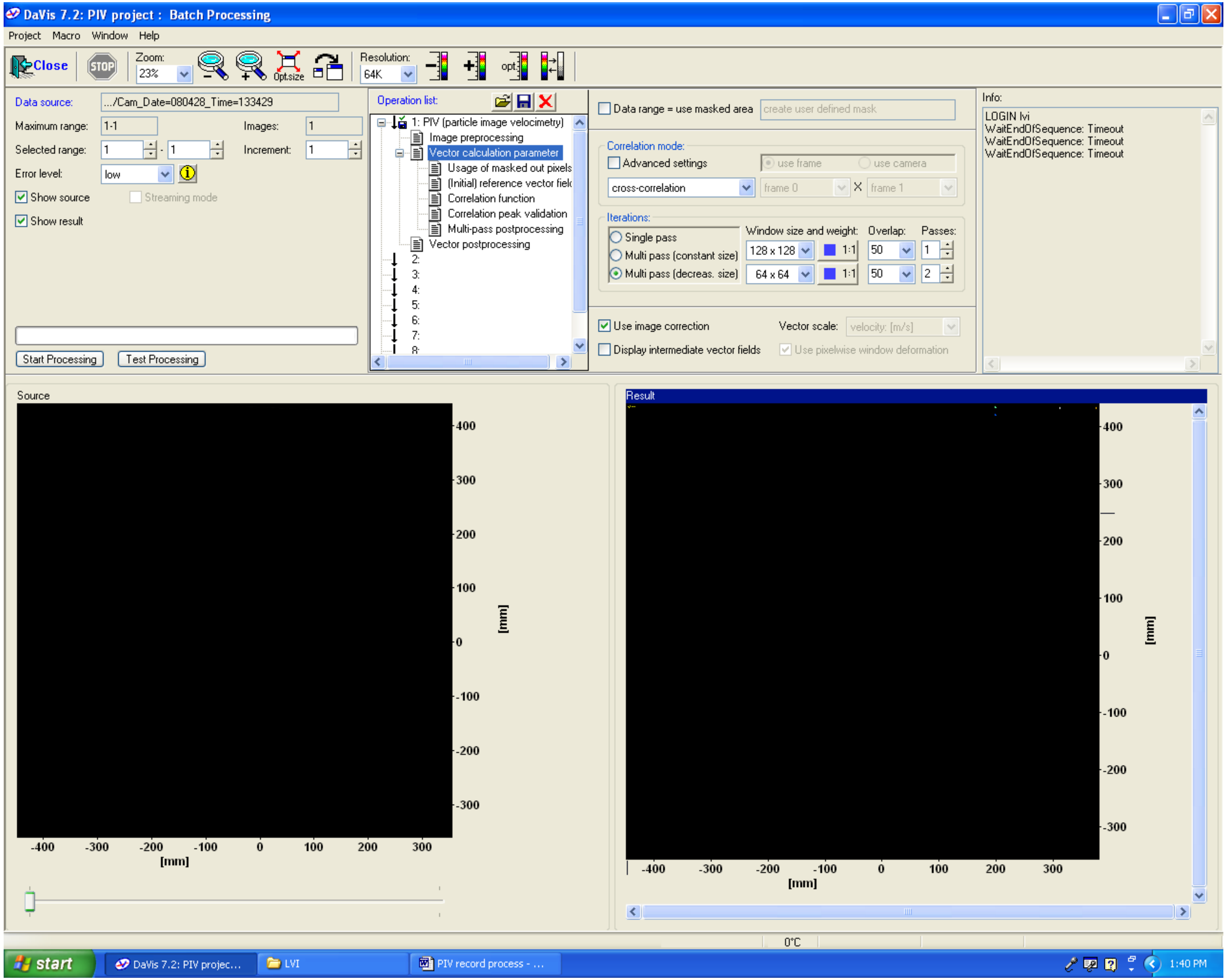
Lavision – DaVis PIV interface

Batch processing



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Demonstration from DaVis vision

https://www.youtube.com/watch?v=VvuIJUl6iqU&t=124s

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Some case studies
with Particle Image Velocimetry (PIV)
Part II

Transonic Flows

PIV Challenges and Advances in High-Speed Wind Tunnel Flows:

Common Challenges
- Limited optical access and image focusing issues due to vibrations and flow density gradients at high velocities
- Short measurement windows

Recent Advances
- Model deformation measurement
- Simultaneous Pressure Sensitive Paint (PSP) and PIV
- Improved synchronization and data quality

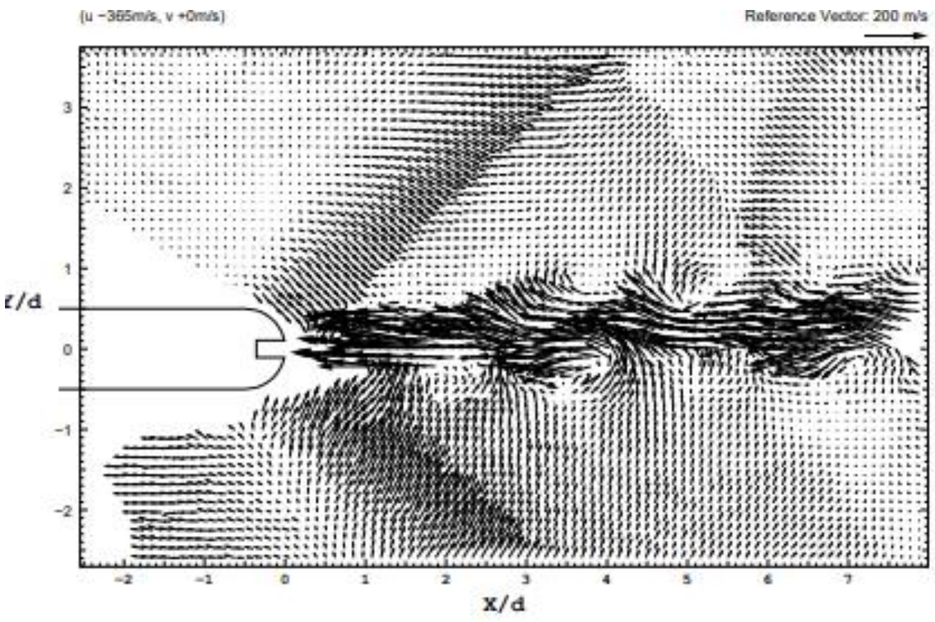

Fig. 9.12. Flow velocity (top) and vorticity field (bottom) behind a cascade blade at $Ma = 1.27$ and a cooling mass flow rate of 1.4%.

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Some case studies with
Particle Image Velocimetry (PIV)
Part III

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Stereo PIV Applied to a Vortex Ring Flow

Imaging Configuration and Hardware

- Imaging Arrangement:
  - Dual-camera setup: Cameras positioned on both sides of the light sheet (~ 35° from normal), combined opening angle ~ 70°.
  - Advantage: Maximize forward scattering from 1 μm oil droplets for enhanced particle visibility and enables full 3D PIV field coverage.
- Cameras & Synchronization:
  - CCD sensors
  - Synchronization: Multi-channel sequencer
- Illumination:
  - Nd:YAG laser (frequency doubled, double oscillator): >300 mJ/pulse.
  - Light sheet thickness: ~ 2.5 mm.

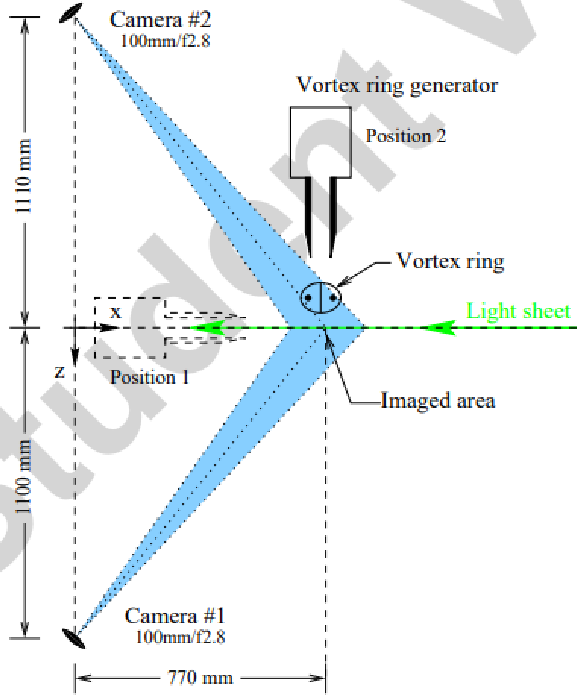

Fig. 9.19. Stereoscopic imaging configuration in forward scattering mode for both cameras.

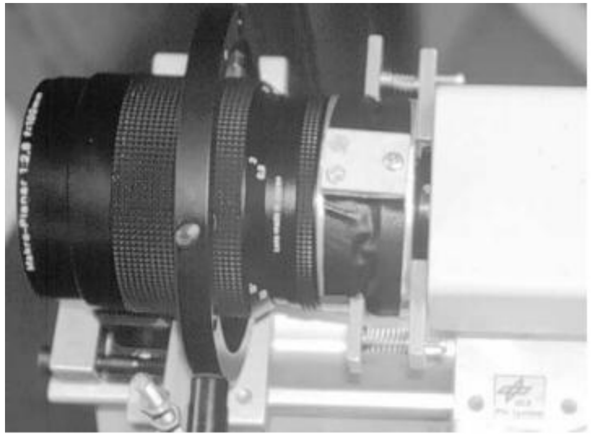

Fig. 9.20. A specially built tilt-adapter between the lens and the sensor allows adjustment according to the Scheimpflug criterion.

Discussions

What are airflow patterns in your project?

Whether PIV may be used in your own project?

What may be challenges using PIV in your project?

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Conclusions

Study Summary

This lecture introduce the concept of PIV, how to perform PIV measurement, particle seeding light sources in PIV, PIV Image Recording and Procession, and a few case studies.

PIV Capability

PIV is a robust, non-intrusive tool capable of capturing whole-field turbulent structures that are invisible to traditional point-measurement techniques.

Application

- Airflow distribution
- High speed flow field
- Micro scale airflow field
- Various fluids

Practical Application

The findings and experimental data are valuable for validating CFD models and improving the design efficiency of chilled beam systems in modern buildings.

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Reference

- *Guangyu Cao, Markku Sivukari, Kurnitski Jarek, Ruponen Mika and Olli Seppänen. Particle Image Velocimetry (PIV) application in the measurement of indoor air distribution by an active chilled beam. Building and Environment, Volume 45, Issue 9, September 2010, Pages 1932-1940*
- *Guangyu Cao, Markku Sivukari, Kurnitski Jarek, Ruponen Mika. PIV measurement of the attached plane jet velocity field at high turbulence intensity level in a room. International Journal of Heat and Fluid Flow, 31(2010): 897-908.*
- *McNeill, J. , Hertzberg, J. and Zhai, Z. (2013) Experimental Investigation of Operating Room Air Distribution in a Full-Scale Laboratory Chamber Using Particle Image Velocimetry and Flow Visualization. Journal of Flow Control, Measurement & Visualization, 1, 24-32. doi: 10.4236/jfcmv.2013.11005.*
- *Thorgeir Harsem et al. Laboratory Research On Airborne Infection Control in Hospital Operating Rooms. ASHRAE Journal 2025 May.*
- *Dorsa Sadat Rabizadeh, Hui Zhang... Guangyu Cao et al. Experimental Evaluation of Targeted Cooling Solutions to Alleviate Surgeon Heat Stress in Operating Rooms ASHRAE Summer conference 2025 Pheonix.*
- *Raffel, Markus, et al. Particle Image Velocimetry. Springer EBooks, Springer Nature, 1 Jan. 2007. Accessed 24 Apr. 2023.*

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