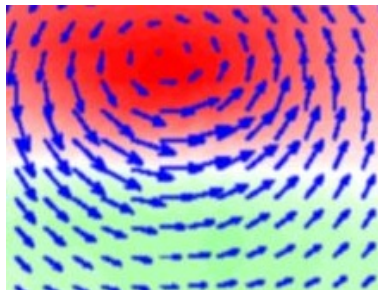


**Master 2 Dynamique des Fluides et Energétique
2019-2020**

Techniques Expérimentales Avancés en Mécanique des Fluides

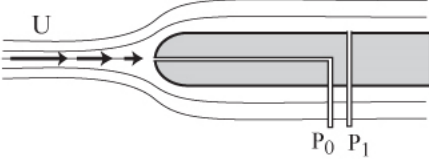
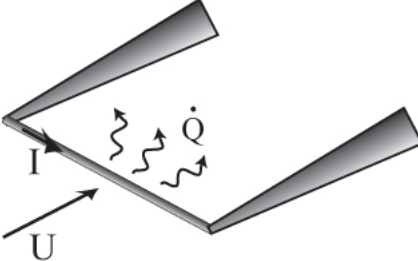
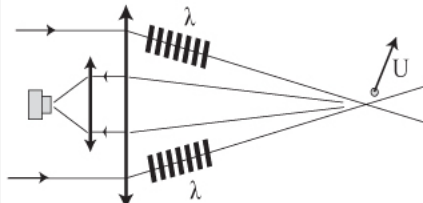
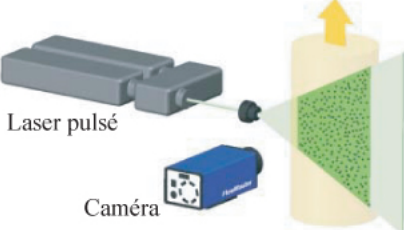
Vélocimétrie par Images de Particules (PIV)

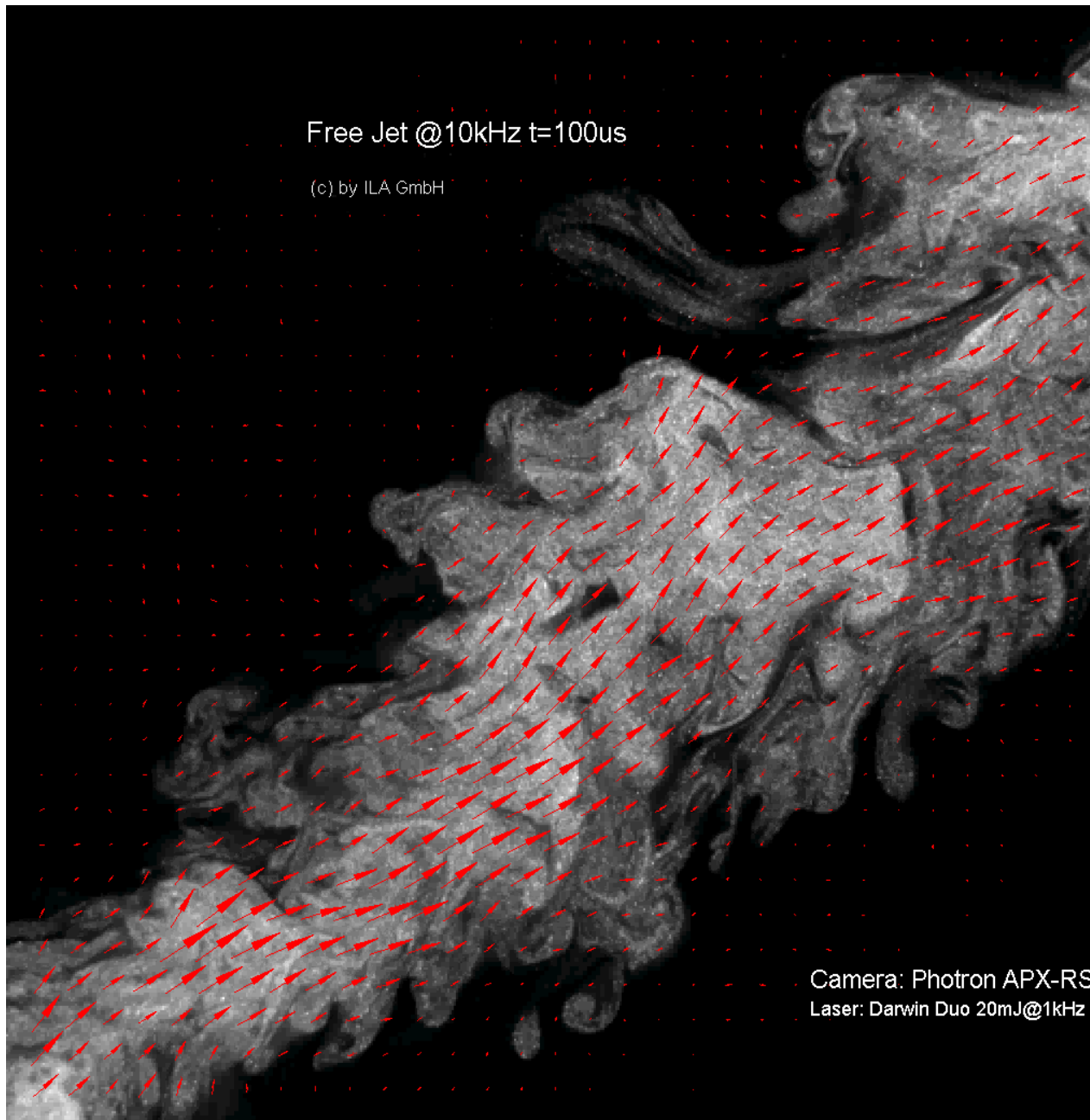


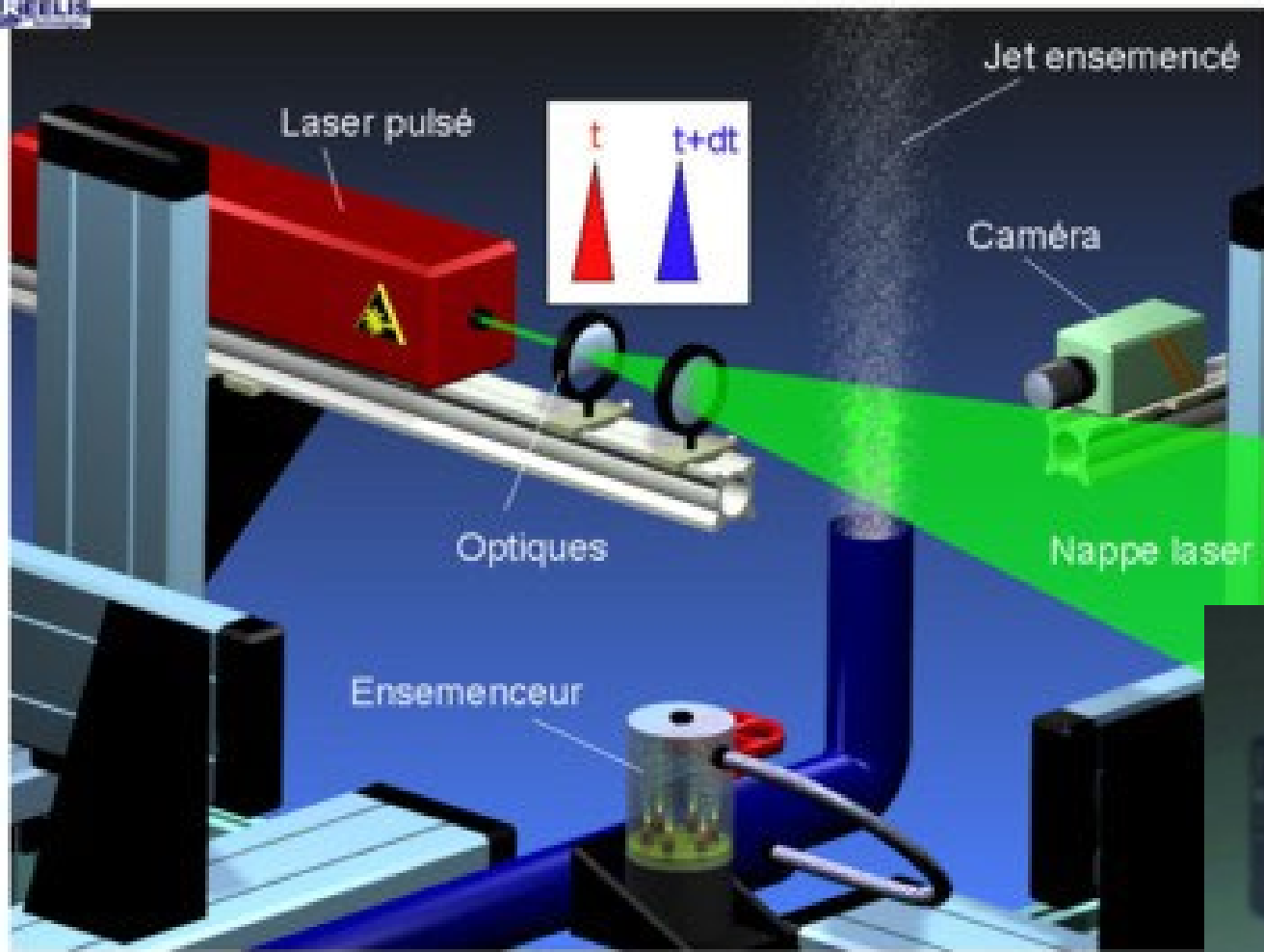
Frédéric MOISY

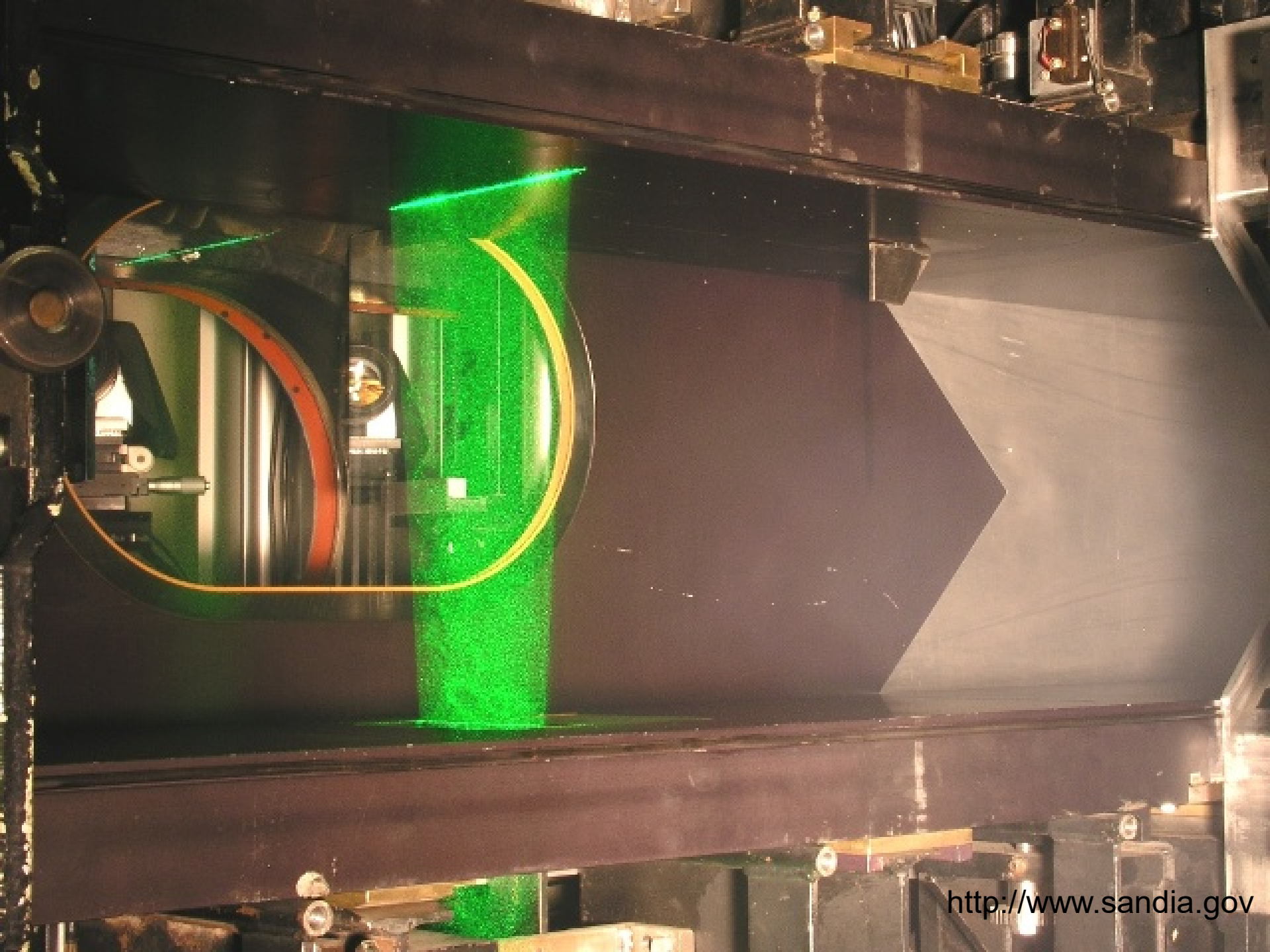
**Université Paris-Saclay
Laboratoire FAST
Bâtiment 530 – 91405 Orsay**

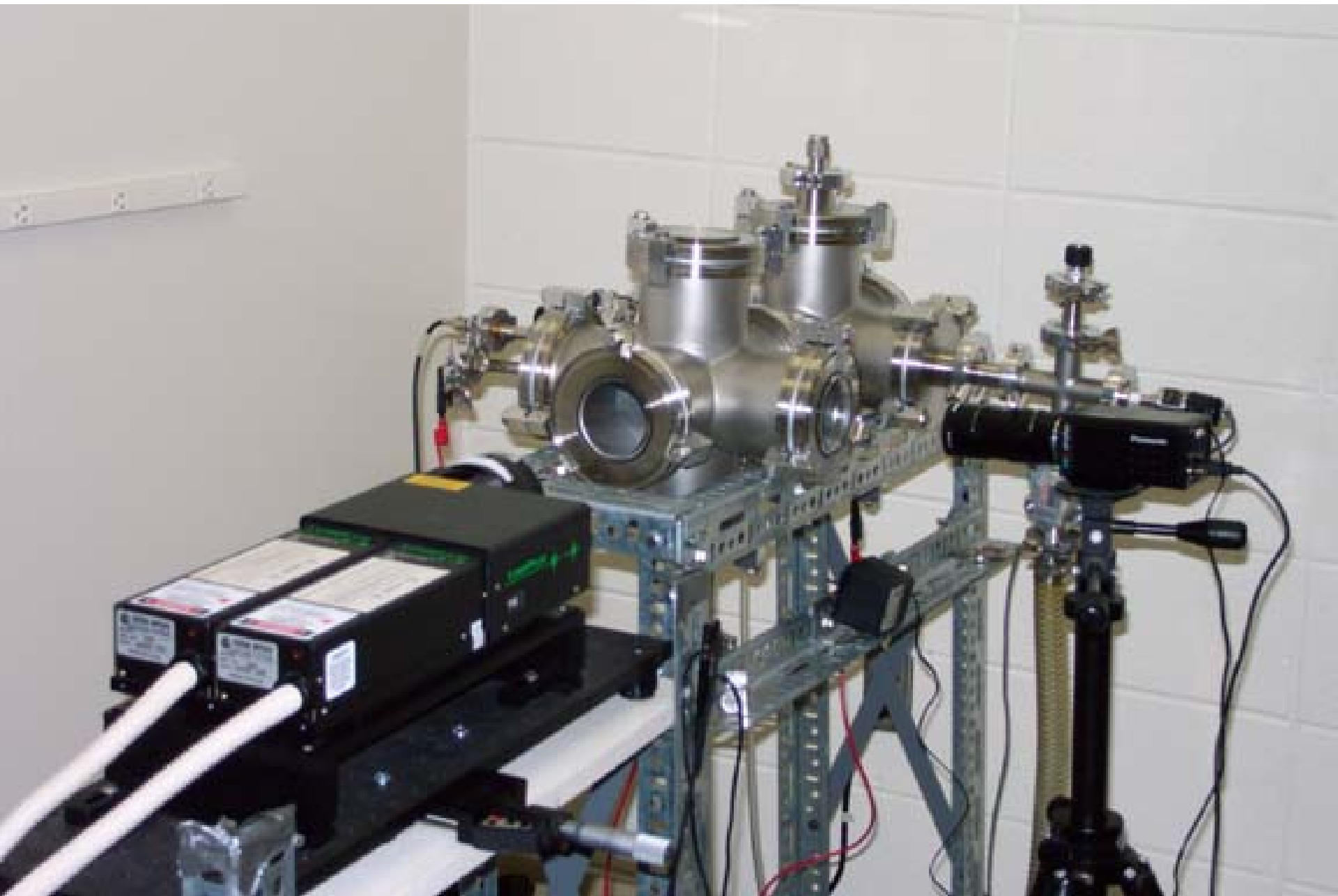
Les mesures de vitesse

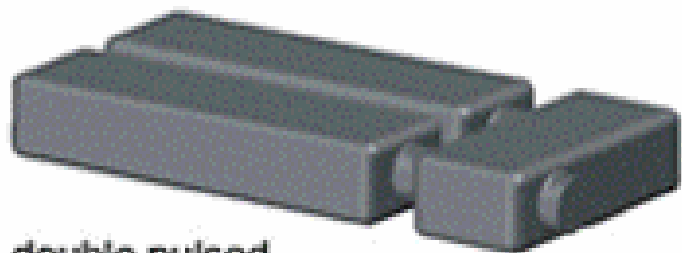
	TUBE DE PITOT	ANEMOMETRE A FIL CHAUD (HOT WIRE ANEMOMETRY)	ANEMOMETRE LASER DOPPLER (LASER DOPPLER VELOCIMETRY, LDV)	VELOCIMETRIE PAR IMAGES DE PARTICULES (PIV)
Schéma				
Principe	Mesure de 2 pressions (statique et dynamique) ? Bernouilli $U = \sqrt{2(P_d - P_s) / \rho}$	Mesure de la puissance RI^2 dissipée par un fil chauffé.	Mesure (par interférométrie) du décalage Doppler sur particule diffusante.	Mesure du déplacement de particules entre deux images (méthode de corrélations)
Avantages	Mise en œuvre très simple, bon marché (~ 1 k€) Idéal pour profils de vitesse moyenne	Excellente résolution spatiale et temporelle (idéal pour mesures de fluctuations turbulentes). Mise en œuvre assez simple, coût modéré (~ 10 - 20 k€).	Non intrusif. Calibration linéaire. Très bonne résolution spatiale et temporelle (idéal pour mesures de fluctuations turbulentes). Possibilité mesure plusieurs composantes.	Non intrusif. Champ 2D instantané.
Inconvénients	Très intrusif. Résolution spatiale & temporelle faible.	Intrusif. Fragile Calibration non linéaire Contaminations (fluct° température)	Accès optique (fluide transparent). Nécessite ensemencement. Réglages délicats. Cher (50-100 k€)	Accès optique (fluide transparent). Nécessite ensemencement. Mauvaise résolution temporelle. Cher (70 - 100 k€)











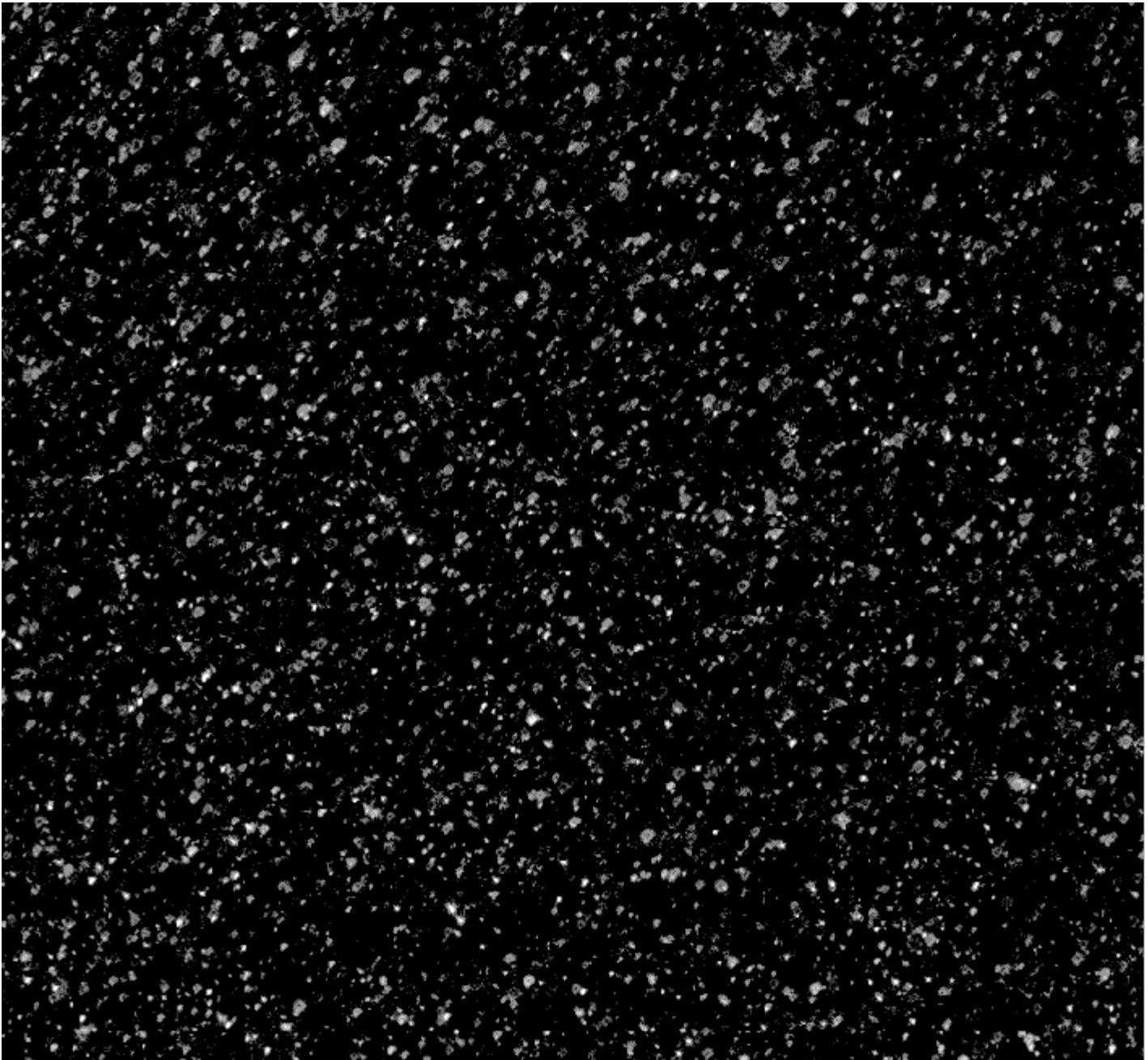
double pulsed
laser

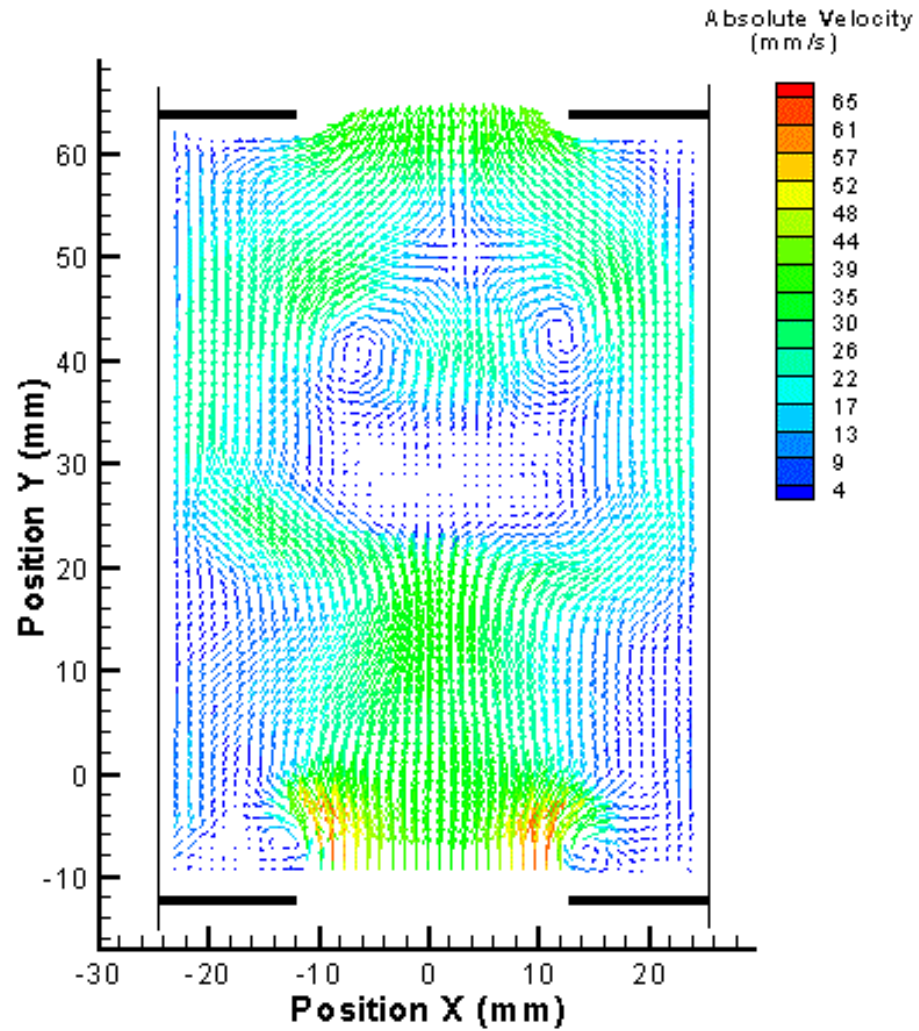
sheet
optics



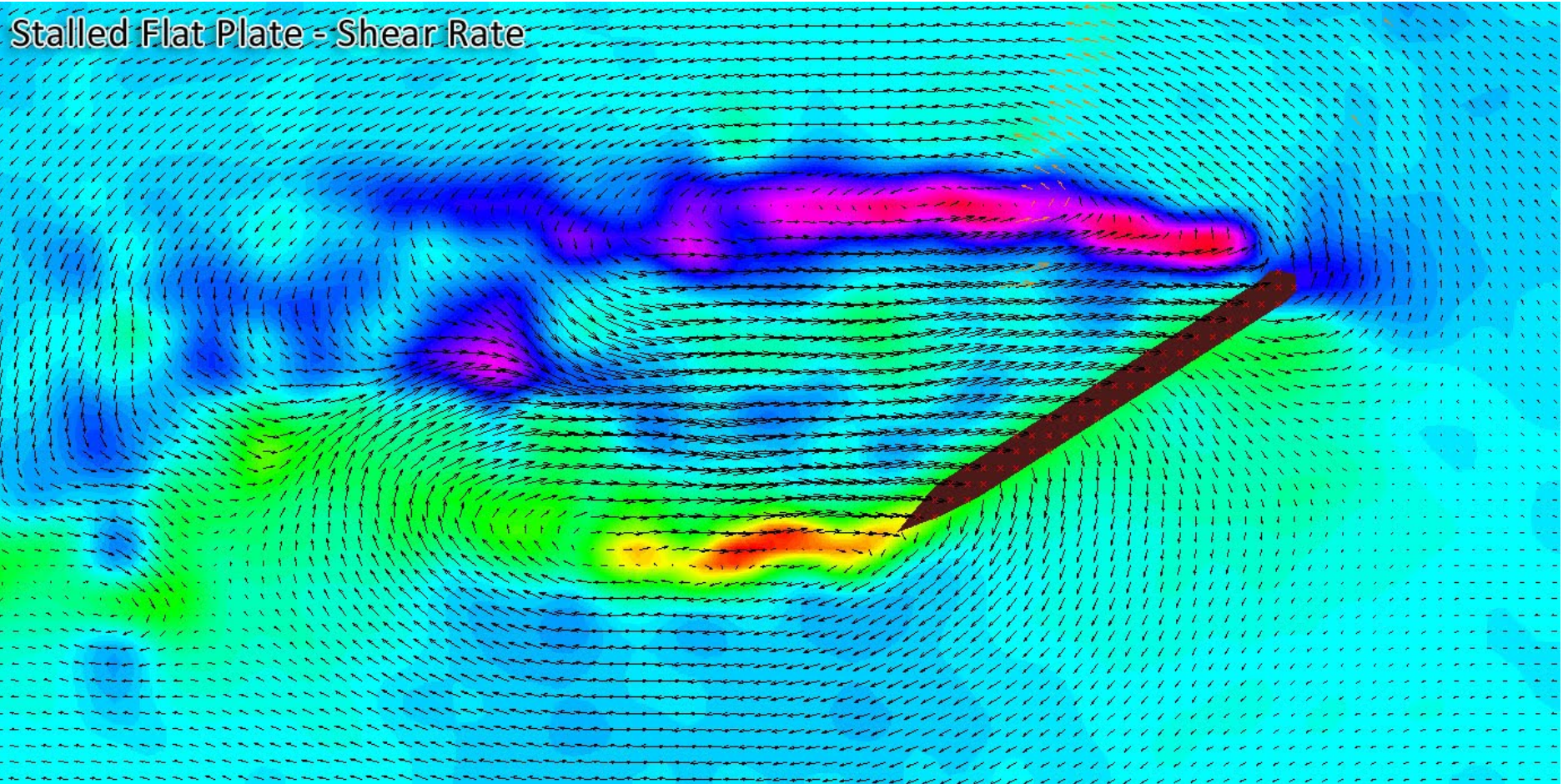
CCD
camera

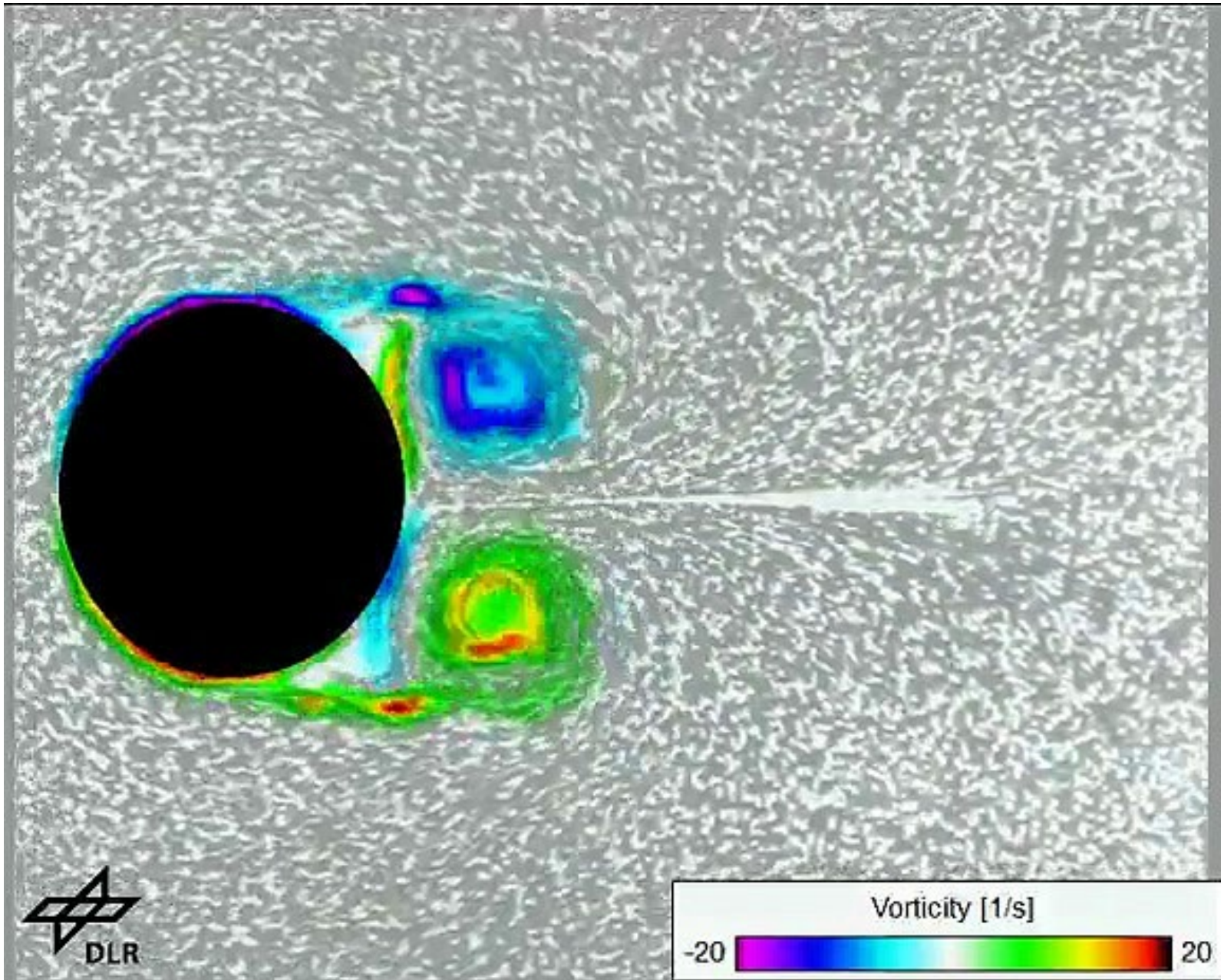






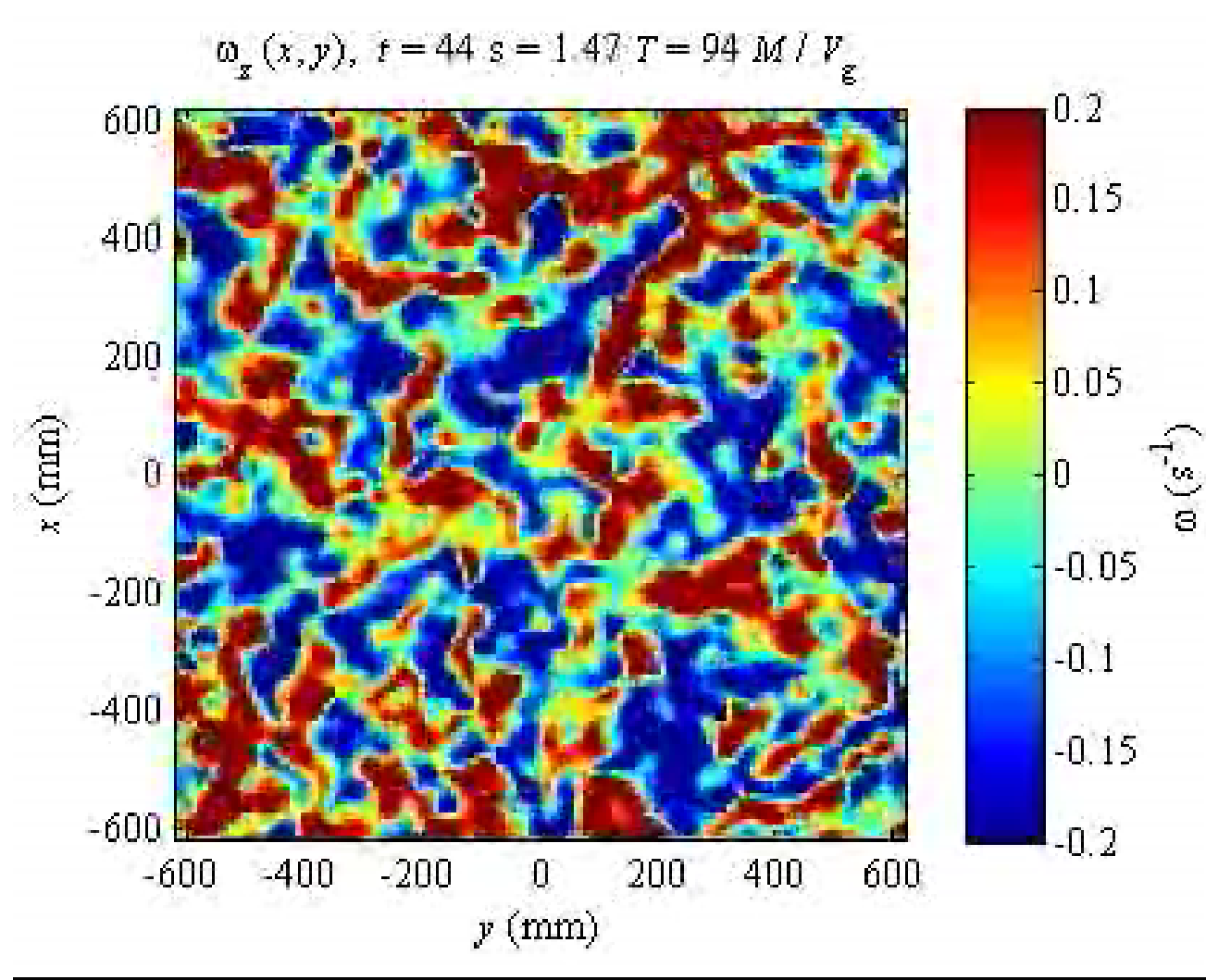
Stalled Flat Plate - Shear Rate





Turbulence en rotation

Collaboration FAST – Coriolis (Grenoble) - 2005



Vélocimétrie par Images de Particules

PLAN

1. Introduction
2. Aspects matériels :
 - 2.1 Particules
 - 2.2 Laser, optique
 - 2.3 Caméras
 - 2.4 Synchronisation
3. Aspects logiciels :
 - 3.1 Corrélation
 - 3.2 Algorithmes avancés (itératifs)
 - 3.3 Post-processing (filtrages)
 - Analyse
4. Développements récents
 - PIV stéréoscopique
 - PIV bi-plan
 - PIV 3D - tomographique
5. Synthetic Schlieren

2.1 - Ensemencement : billes de verres creuses

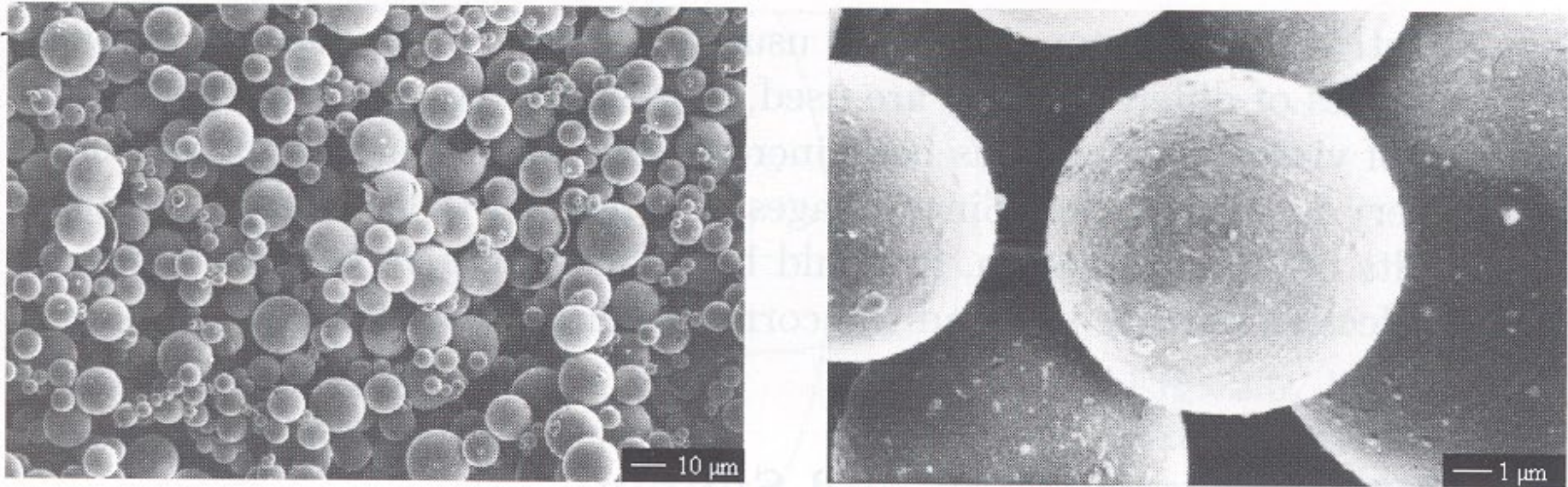


Fig. 2.8. Micrographs of silver coated hollow glass spheres: $\times 500$ and $\times 5000$.

Ensemencement : choix de particules

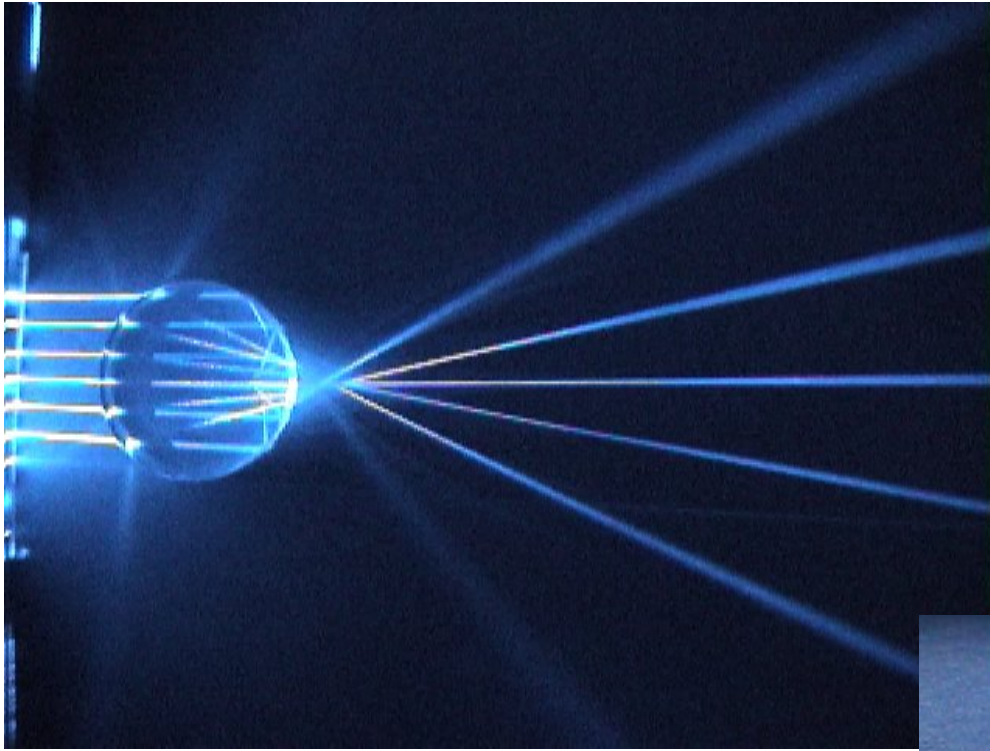
Particules pour l'eau

	Diamètre	Densité	Tps réponse
Billes de verre creuses	10 μm	1.1 g/cm^3	0,5 μs
Poudre aluminium	3 μm	2.7 g/cm^3	0,9 μs

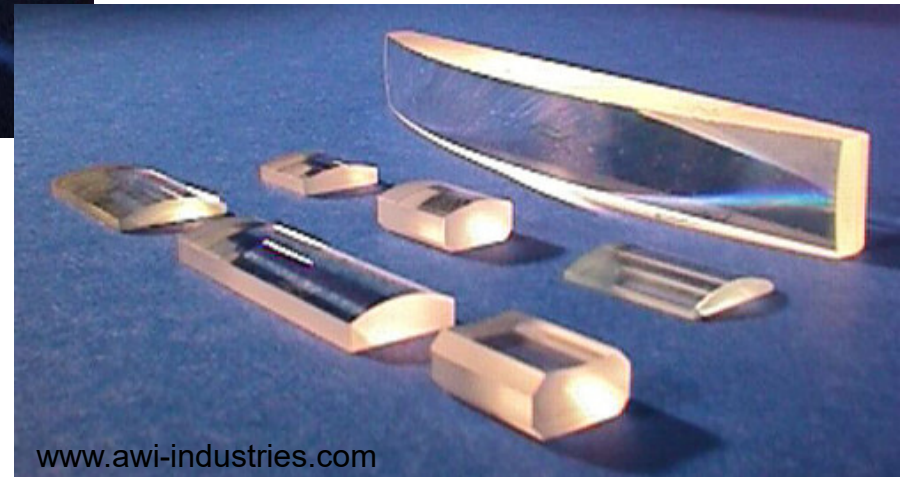
Particules pour l'air

Gouttes d'huile	1 μm	0.92 g/cm^3	0,3 μs
Billes SiO_2	0.8 μm	2.6 g/cm^3	5 μs

2.2 - Optique pour nappe laser

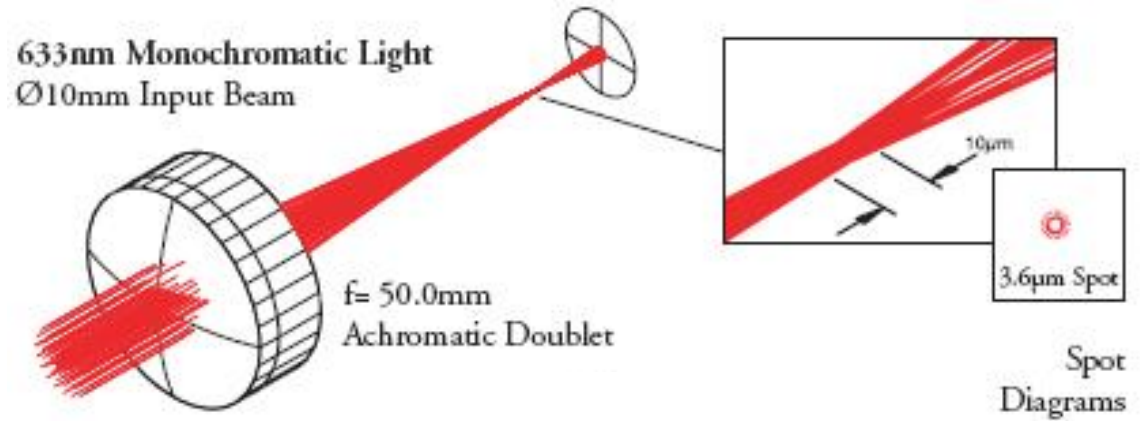


Réfraction par une
lentille cylindrique



Optique pour nappe laser

Réglage épaisseur



Dantec



Oxford laser

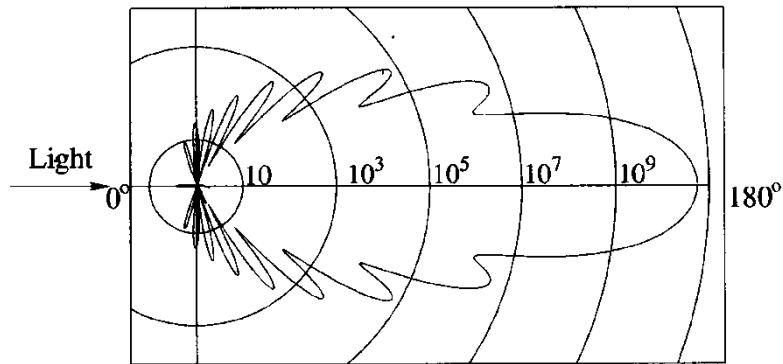


Fig. 2.5. Light scattering by a 1 μm glass particle in water.

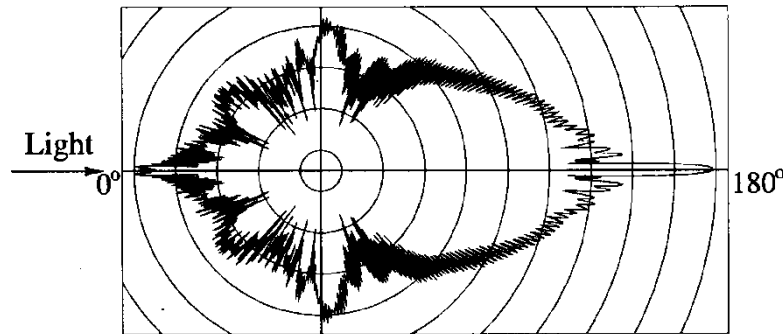


Fig. 2.6. Light scattering by a 10 μm glass particle in water.

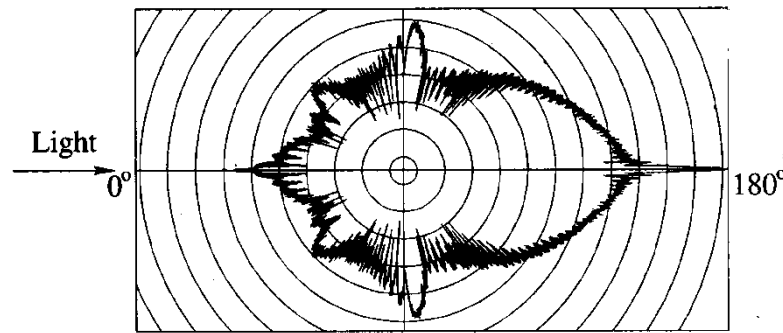
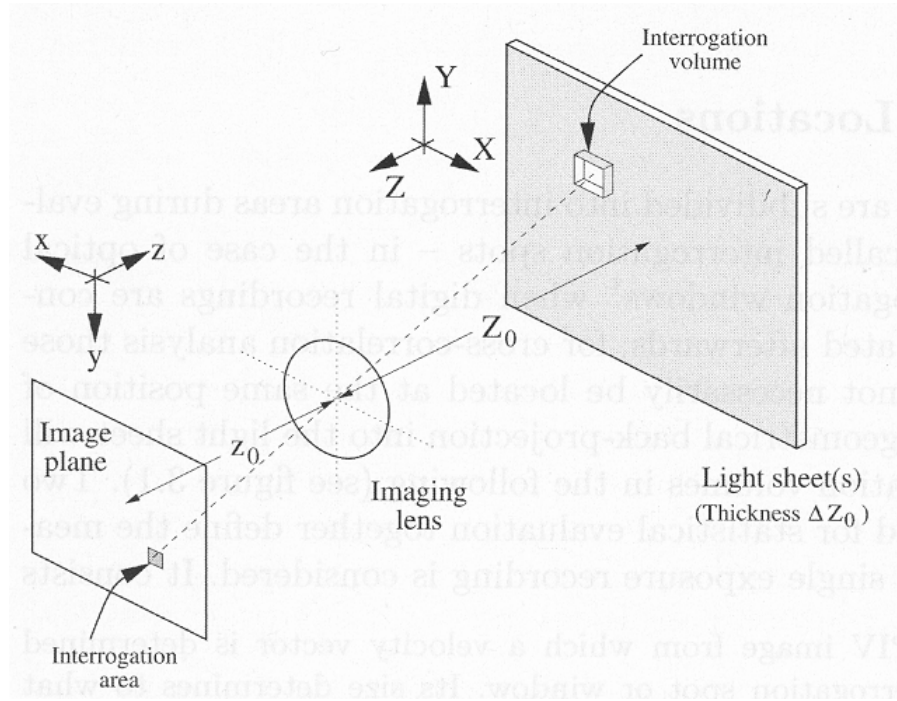
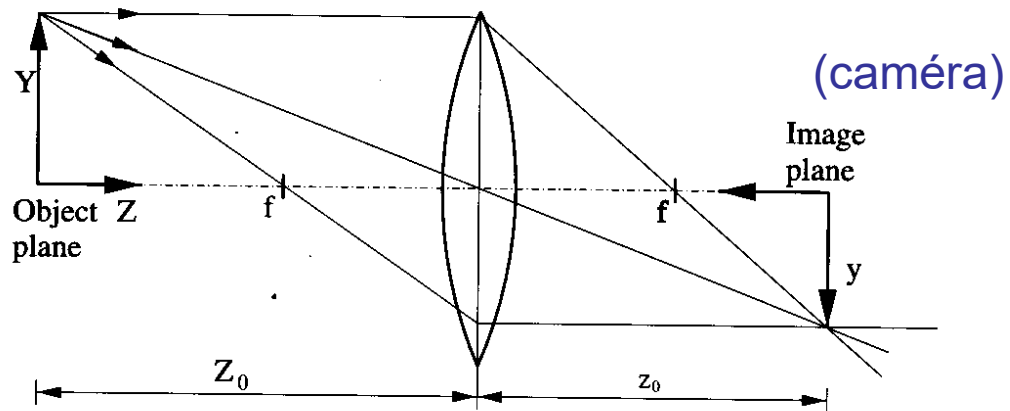


Fig. 2.7. Light scattering by a 30 μm glass particle in water.

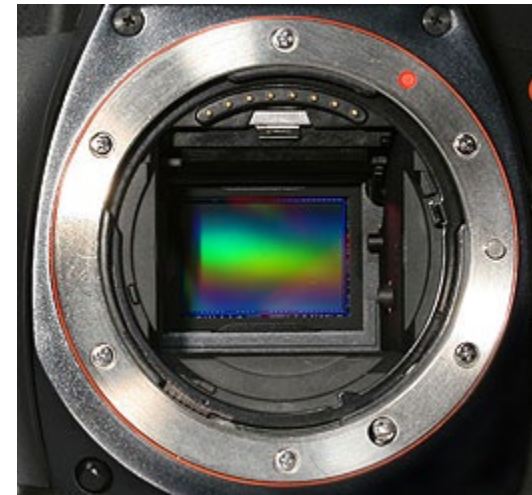
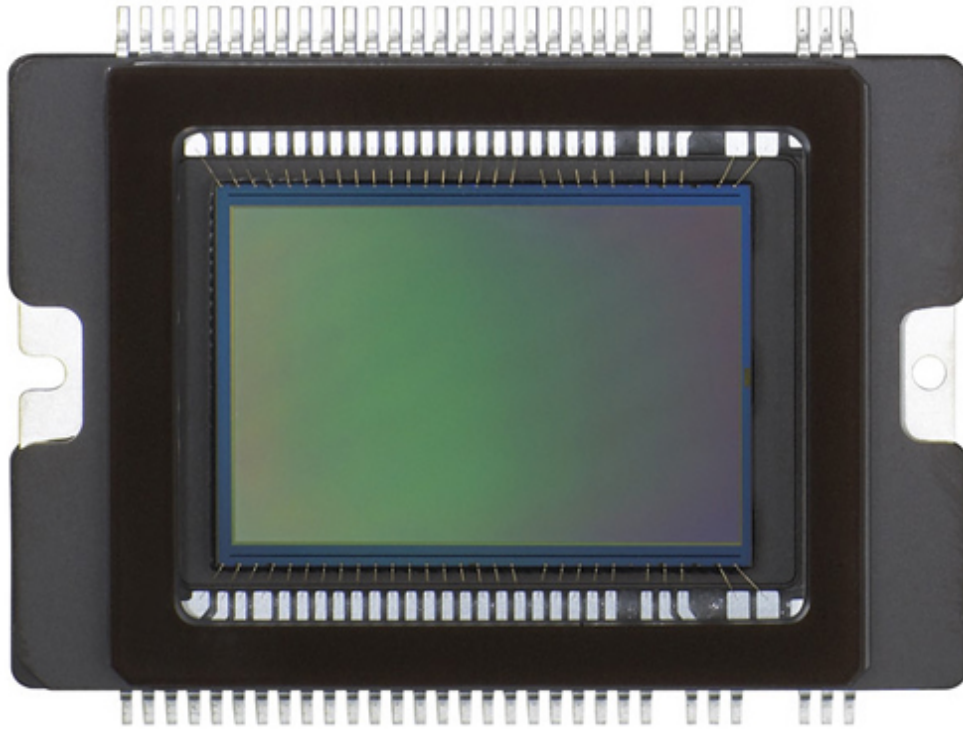
Visualisation



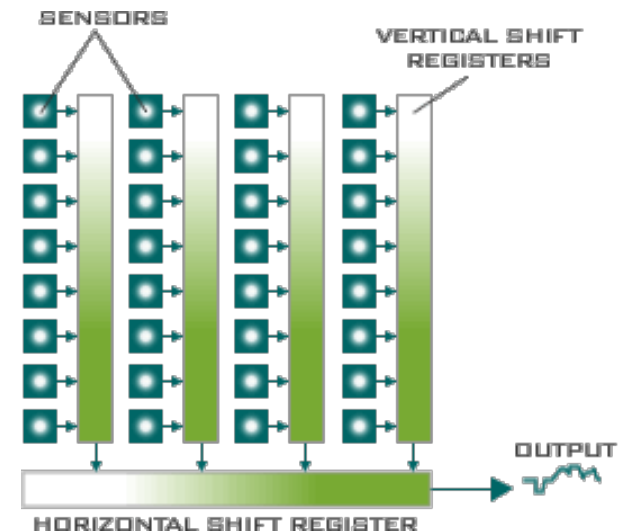
Agrandissement :
 $M = y / Y$
 = image/objet (< 1)



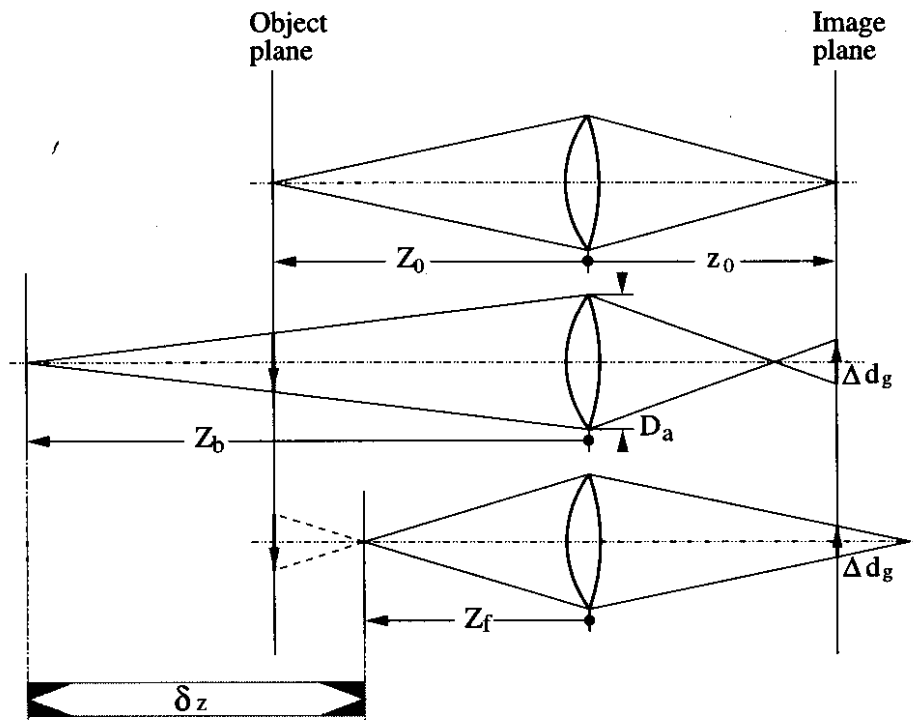
Capteurs CCD



Résolutions :
1000x1000 à ~ 5000x4000



Profondeur de champ

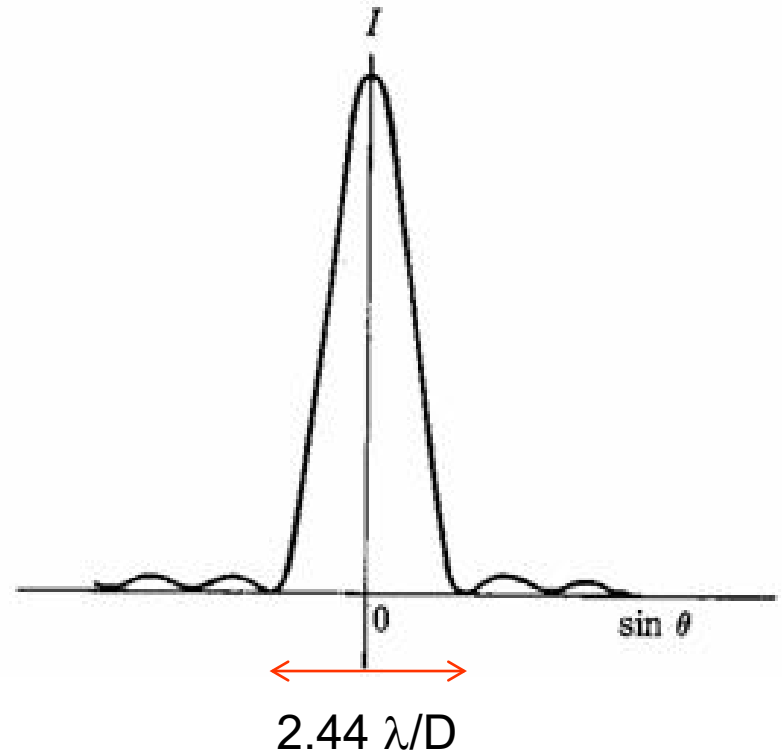
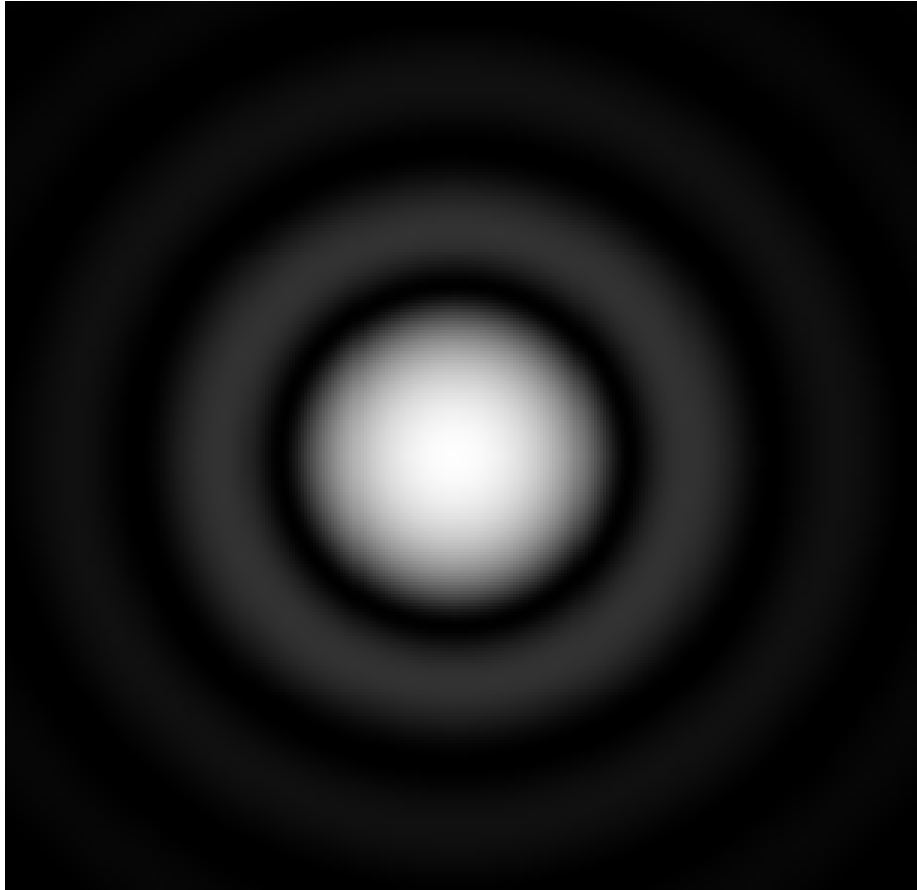


Application Micro-PIV



Limite de diffraction

Tâche d'Airy



Erreurs de perspective

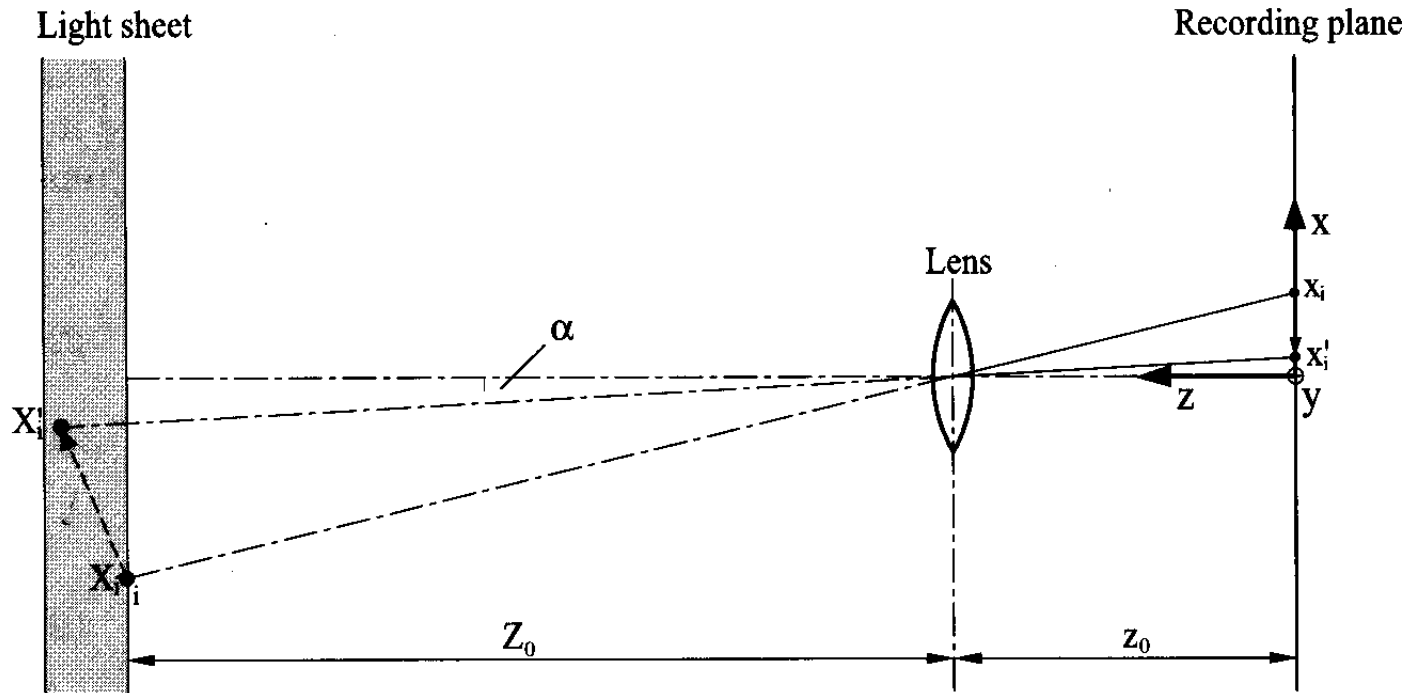


Fig. 2.37. Imaging of a particle within the light sheet on the recording plane.

Lasers

Lasers continus

Puissance typique : 0.5 – 5 W (5-50 keuros)

(1 W donne 30 mJ par image
à 30 images/s)

Lasers pulsés

Durée pulse : 10 – 100 ns

Energie par pulse :

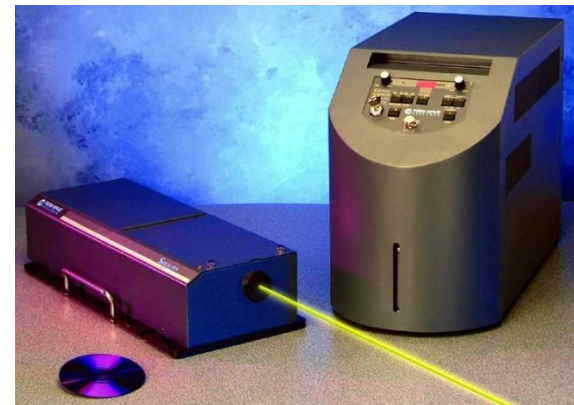
- expé. Eau : 10 – 100 mJ (20-30 keuros)
- expé Air : 50 – 500 mJ (80-100 keuros)

Fréquences :

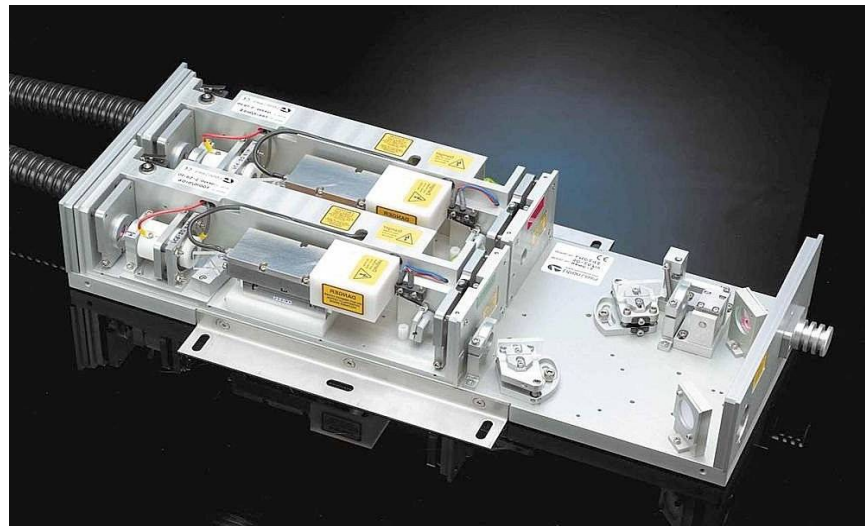
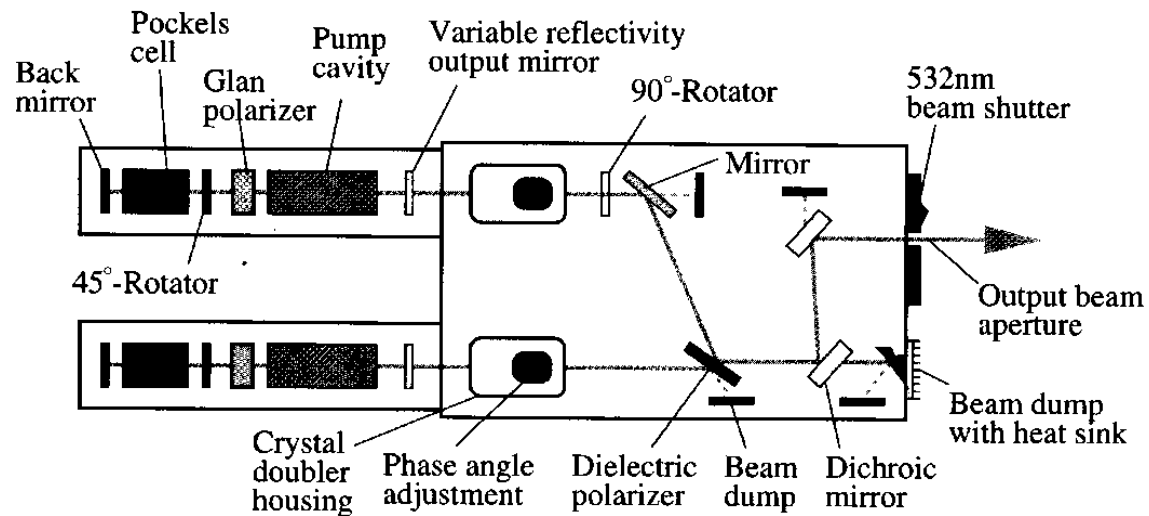
- Basse cadence (10-30 Hz)
- Haute cadence (1 – 10 kHz)

MINILITE™ PIV SPECIFICATIONS

DESCRIPTION	MINILITE™ PIV
Repetition Rate (Hz)	1-15
Energy (mJ)	
1064 nm	50
532 nm	25
Pulsewidth ¹ (nsec)	
1064 nm	4-6
532 nm	3-5
Divergence ² (mrad)	< 3
Jitter ³ (±ns)	0.5
Energy Stability ⁴ (±%)	
1064 nm	2; 0.7
532 nm	3; 1.0
Beam Spatial Profile (fit to Gaussian) ⁵	
Near Field (<1 M)	0.70
Far Field (∞)	0.95



Laser pulsé double-cavité

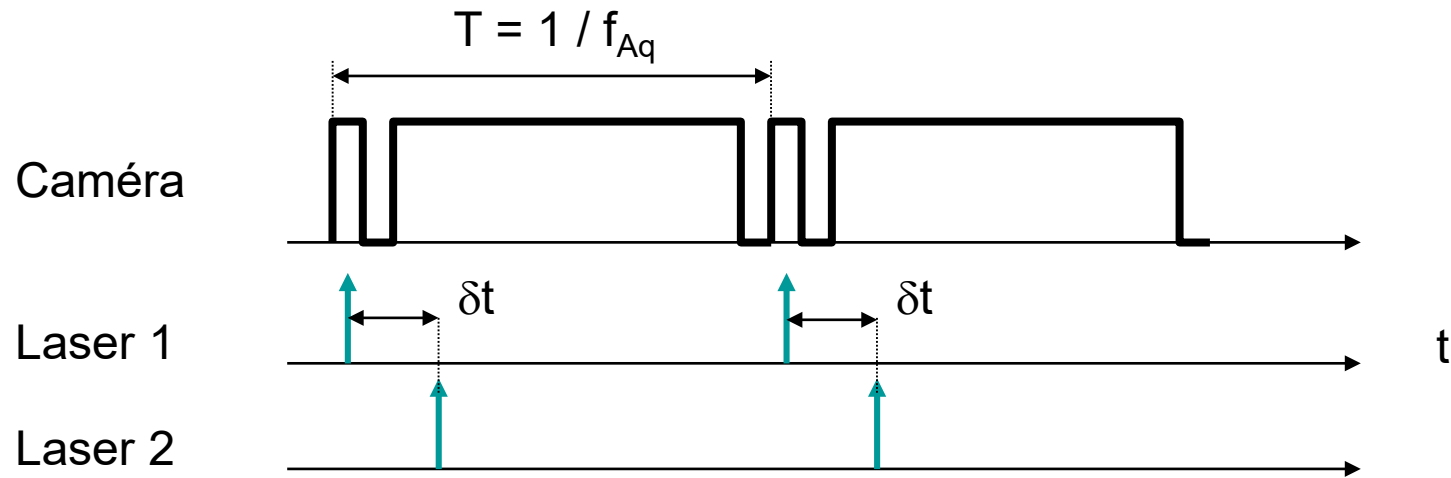


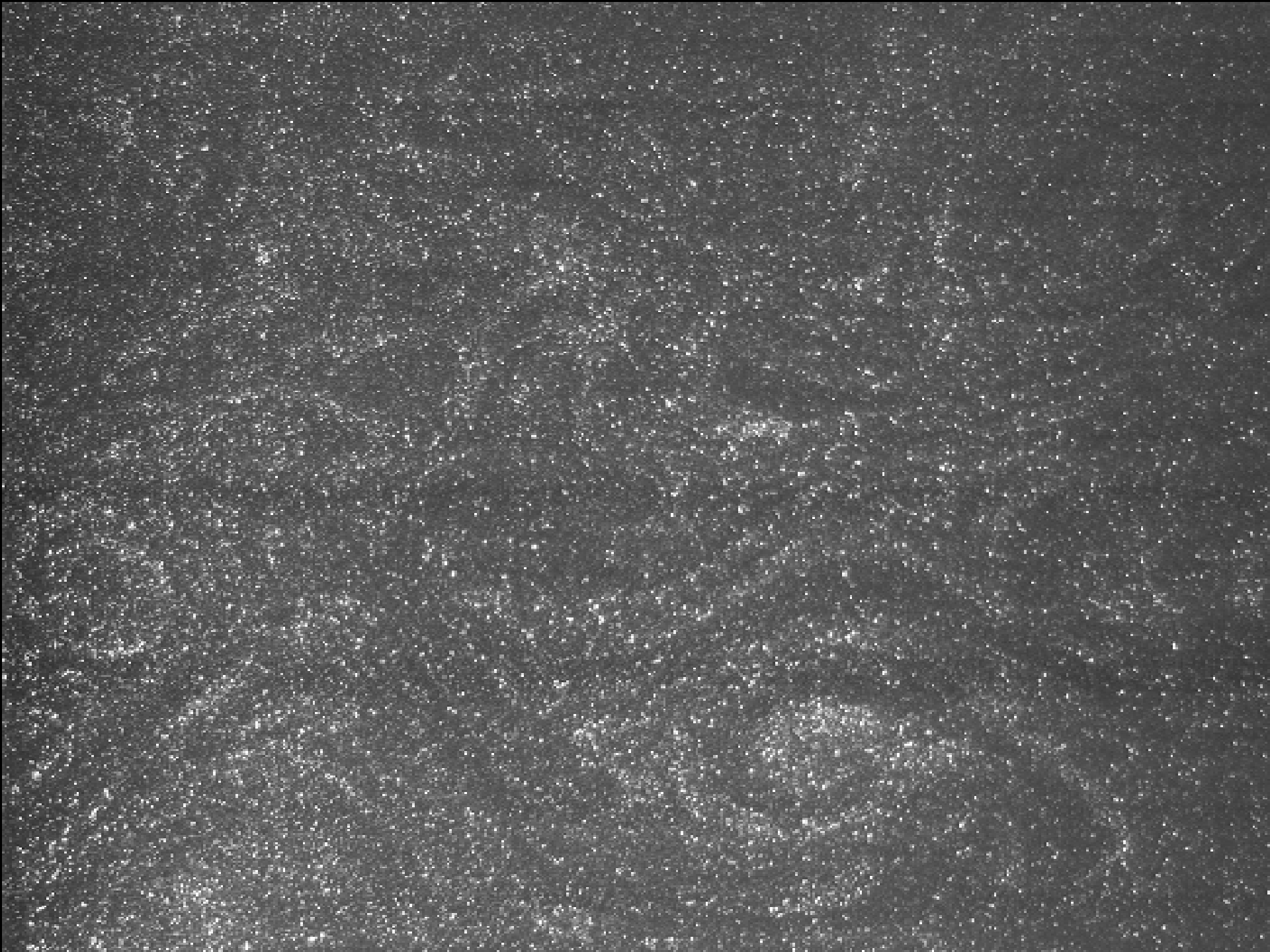
2.3 - Caméras pour PIV

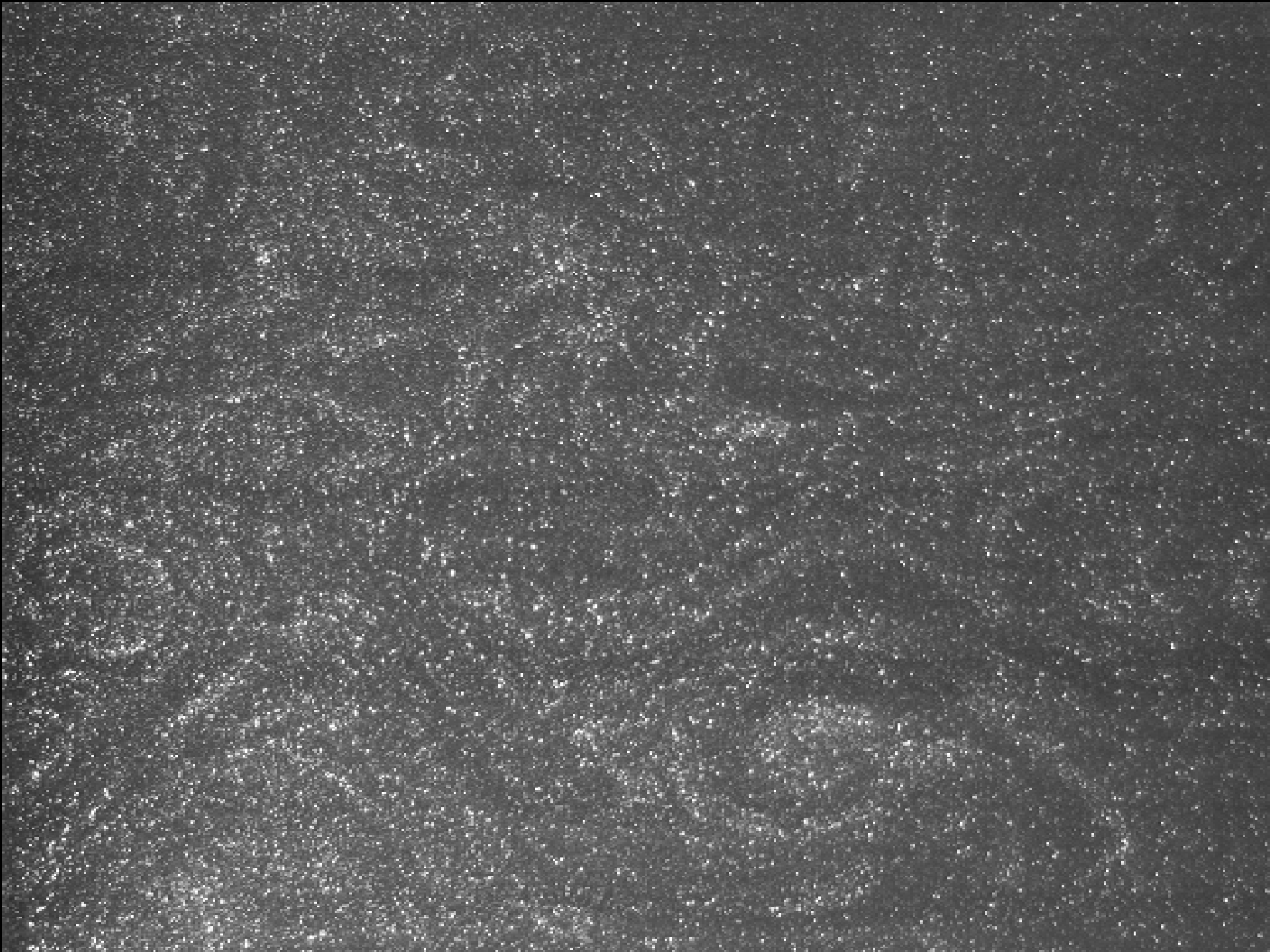


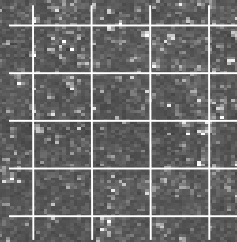
	Caméras standards	Caméra double-frame	Caméras rapides (RAM interne)
Capteur	CCD 10 – 12 bits (1024 à 4096 n.g.)	CCD 12 – 14 bits (4096 à 16384 n.g.)	CMOS 12 bits
Résolution	1000 ² 2000 ² 20 - 100 Hz	1000 ² 2000 ² 2x4 à 2x30 Hz	1000 ² 0.5 à 10 kHz
Prix	0.5-1 k€	5 – 20 k€	20-60 k€

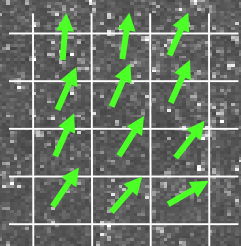
2.4 – Synchronisation : système double-frame

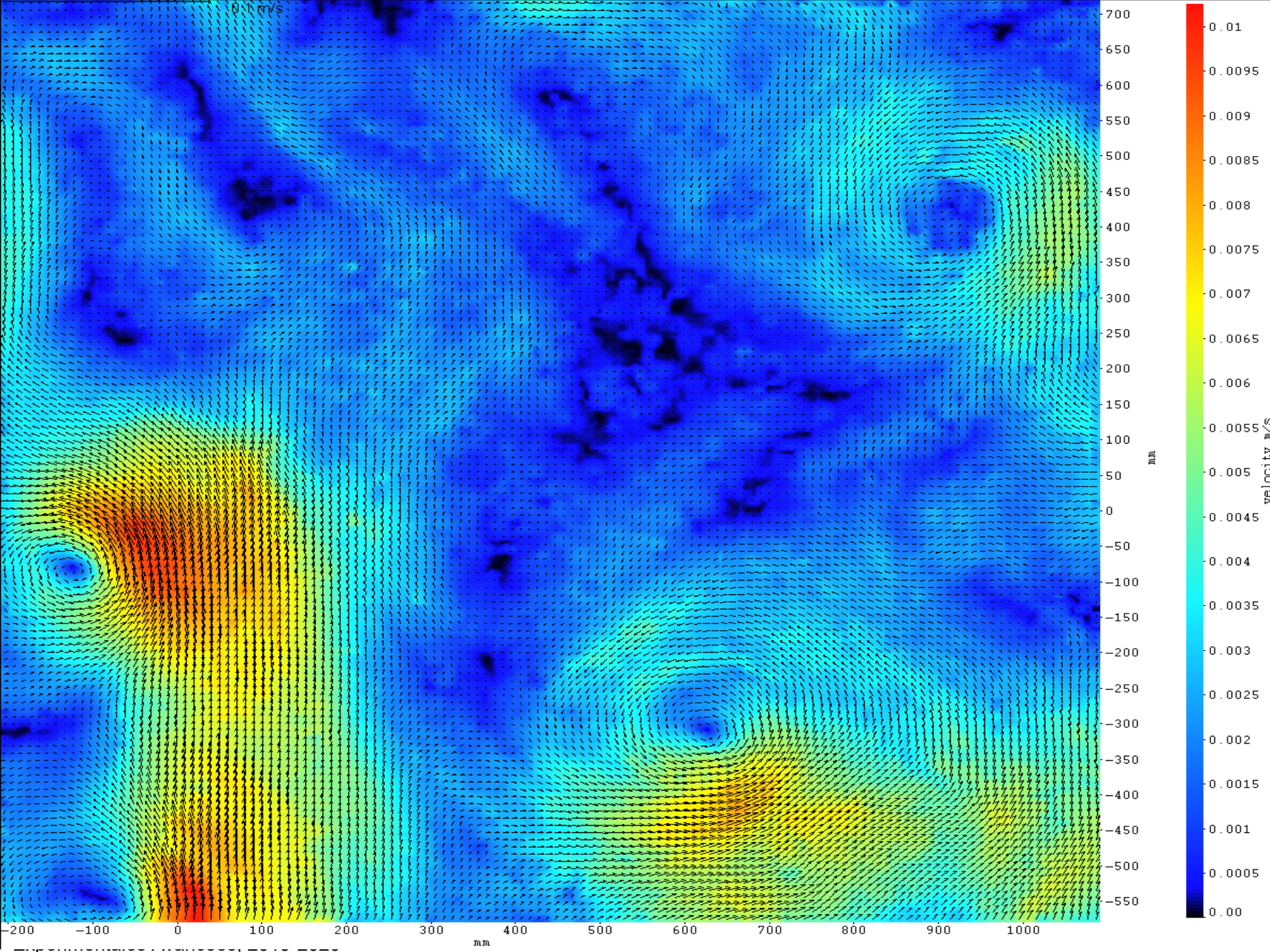




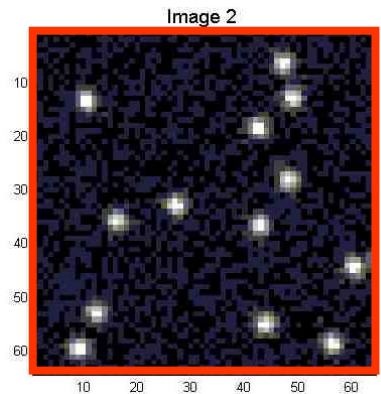
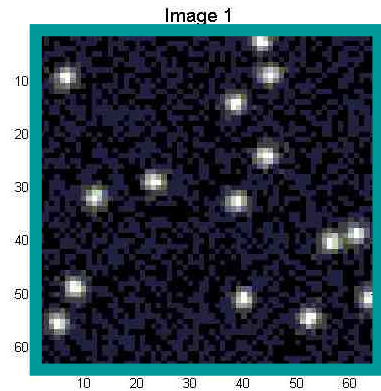




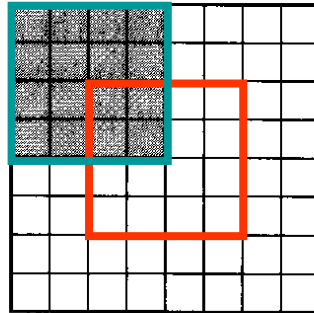




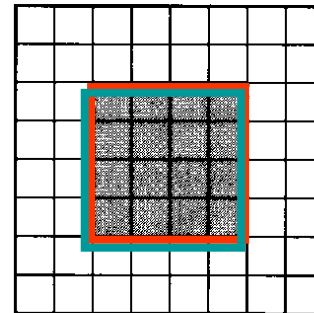
3. Cross-correlation



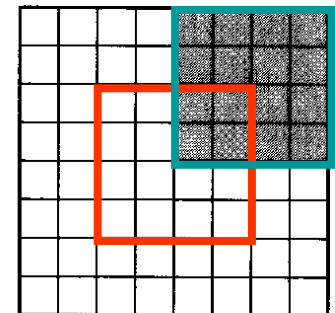
Shift (x=-2, y=2)



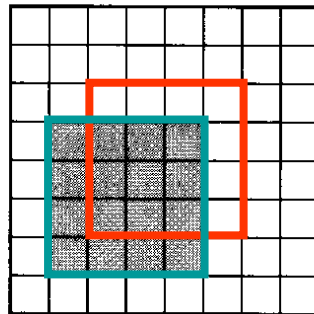
Shift (x=0, y=0)



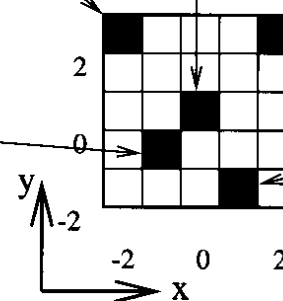
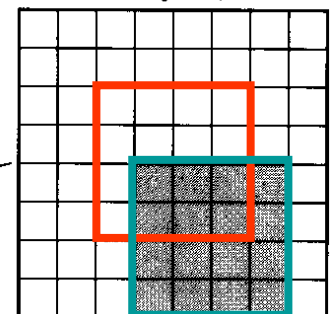
Shift (x=2, y=2)



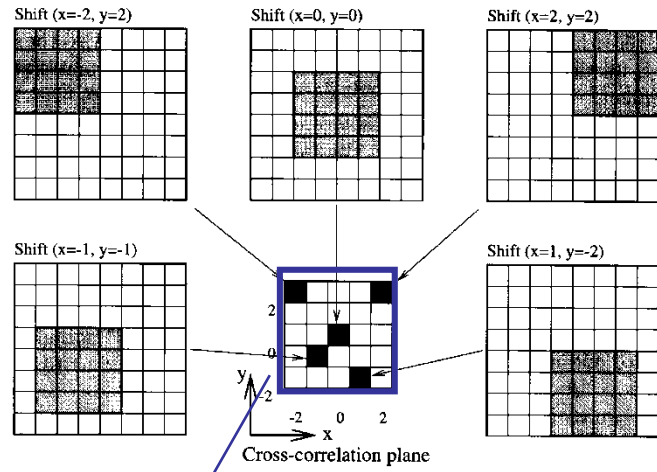
Shift (x=-1, y=-1)



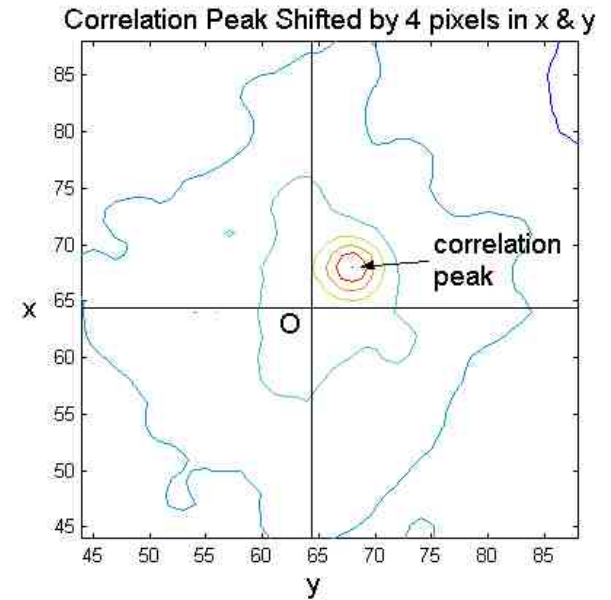
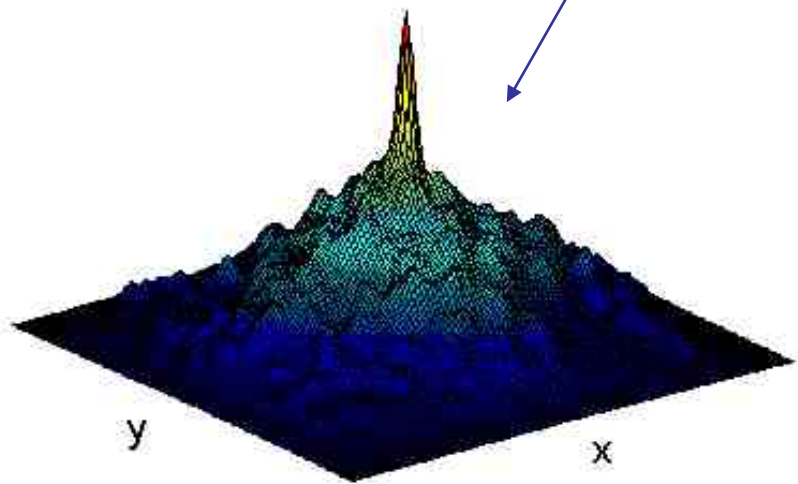
Shift (x=1, y=-2)



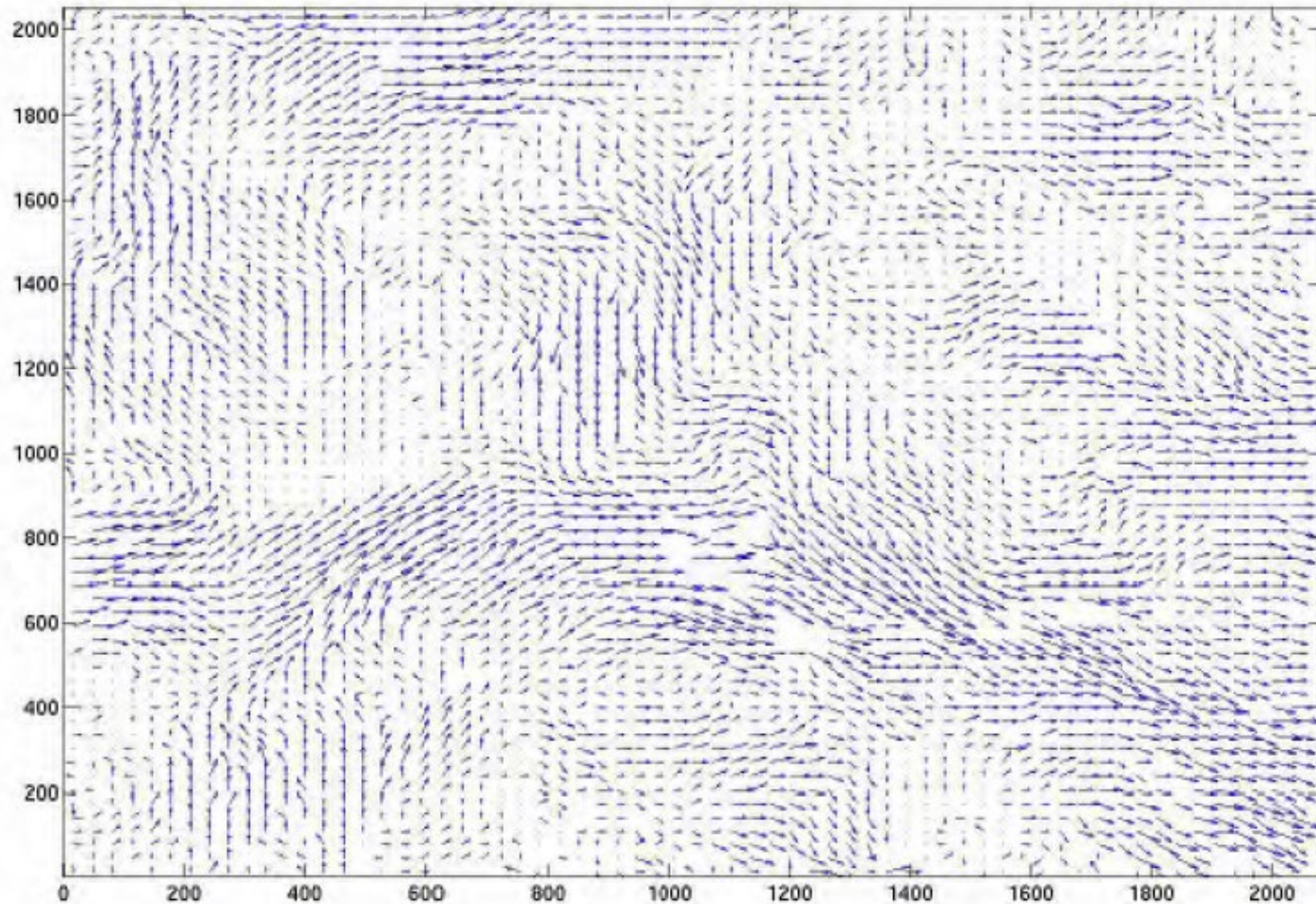
Cross-correlation plane



3D view of the correlation function



Problème de discrétisation : "peak-locking"



Problème de discrétisation : "peak-locking"

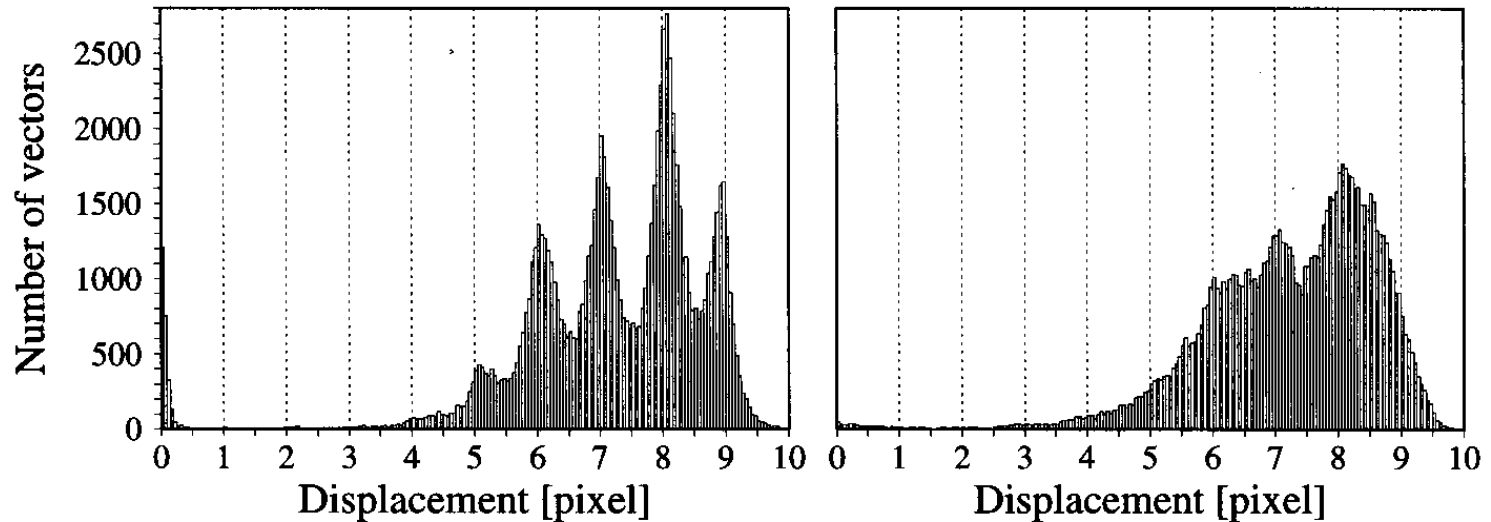
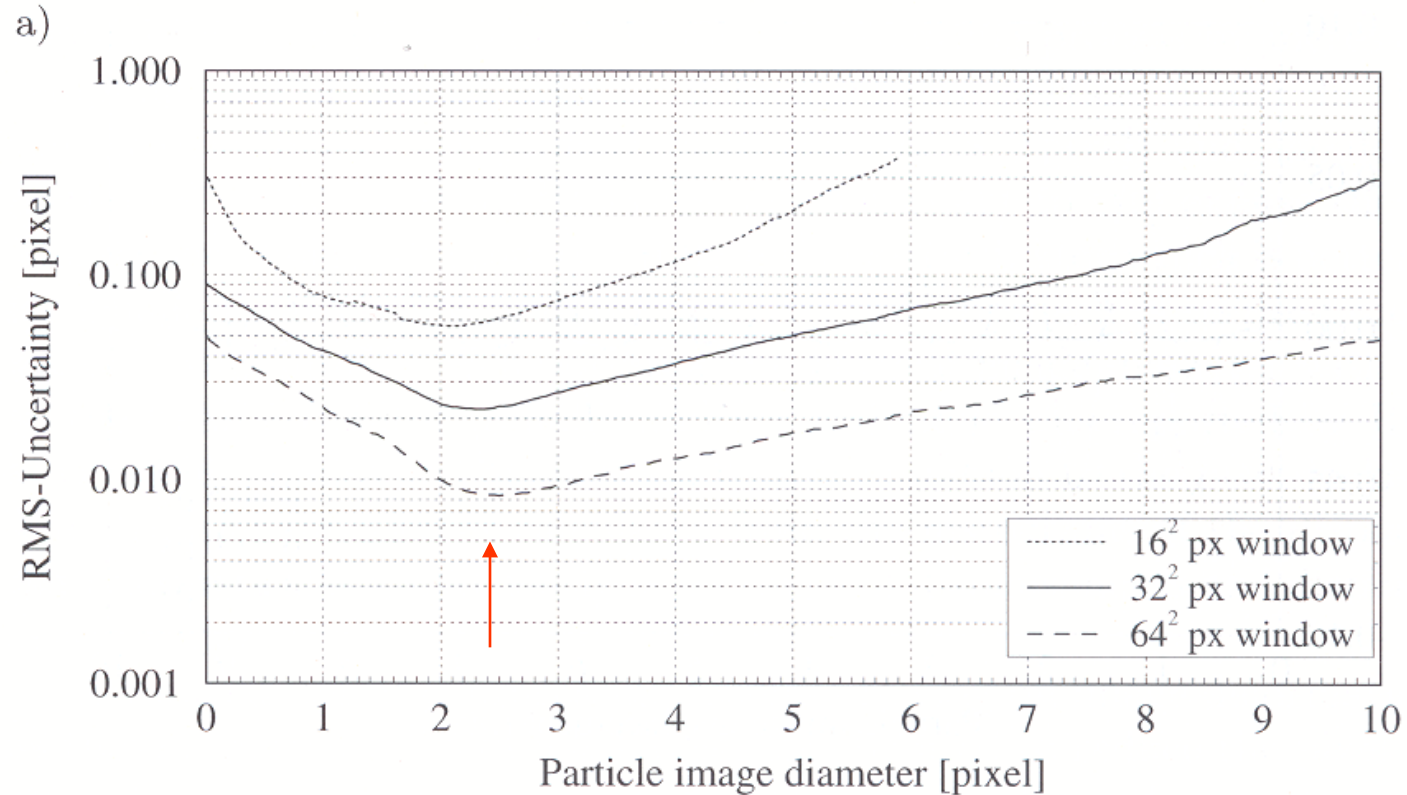


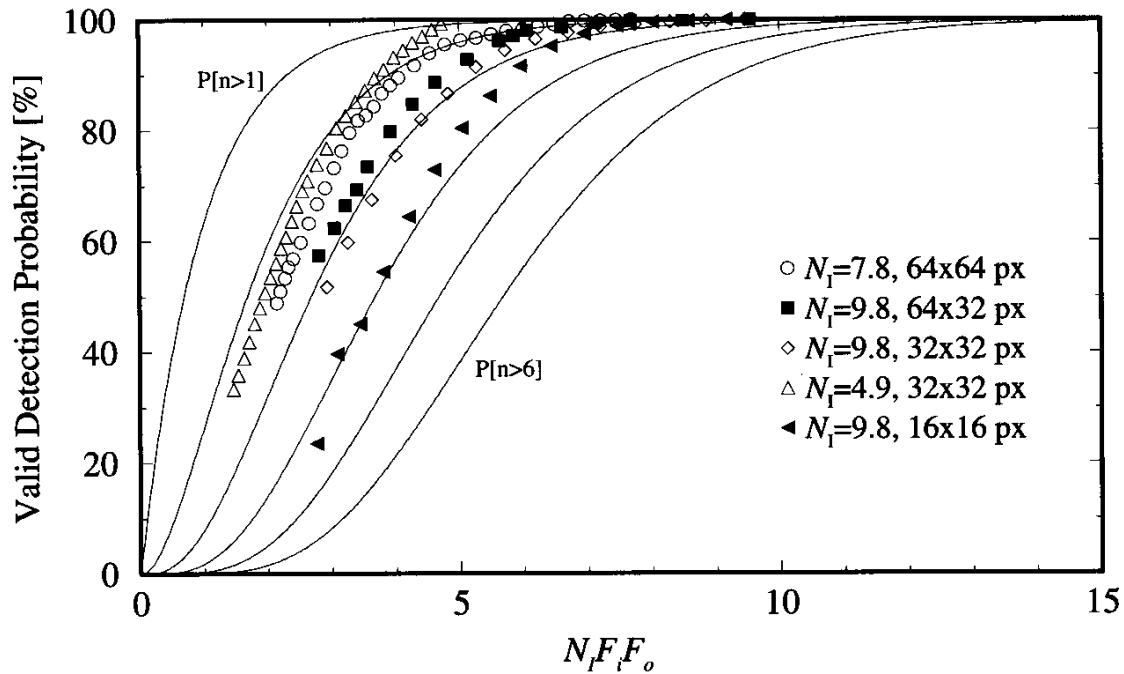
Fig. 5.34. Histograms of actual PIV displacement data obtained from a 10-image sequence of a turbulent boundary layer illustrating the “peak locking” associated with insufficient particle image size (left). Image pre-processing can reduce this effect (right). Histogram bin-width = 0.05 pixel.

Taille optimale des particules



to

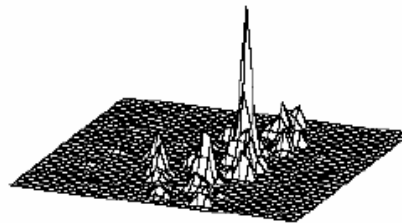
Densité minimale des particules



$N_I = 5$



$N_I = 10$



$N_I = 25$

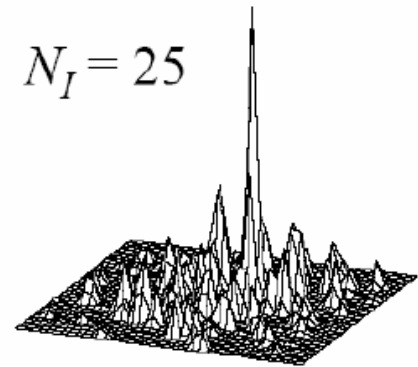
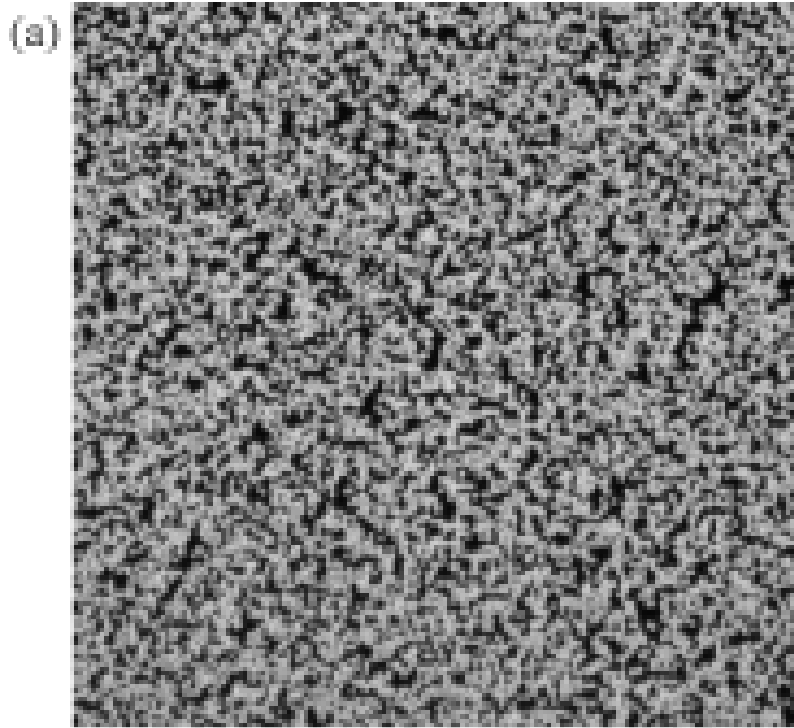
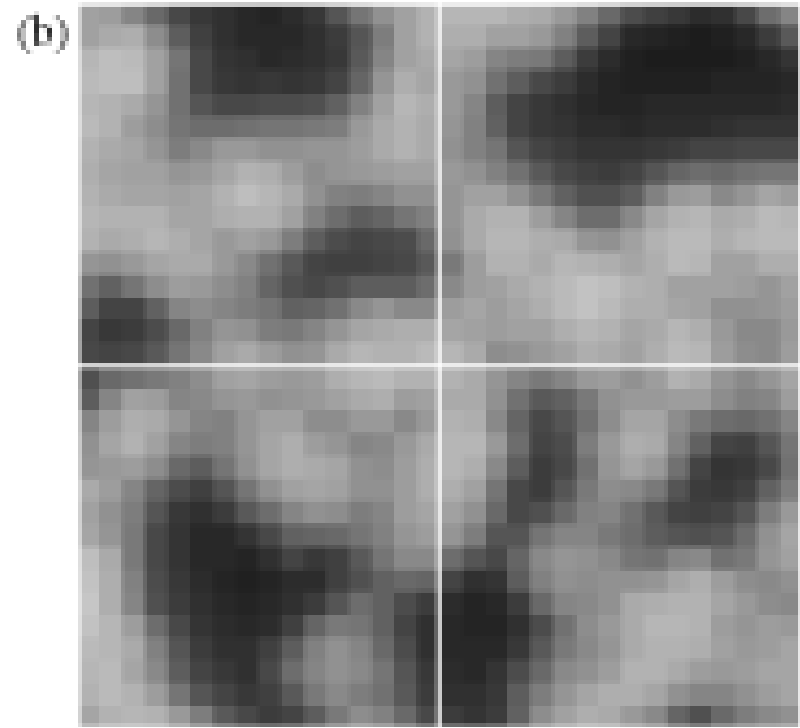


Image « optimale »



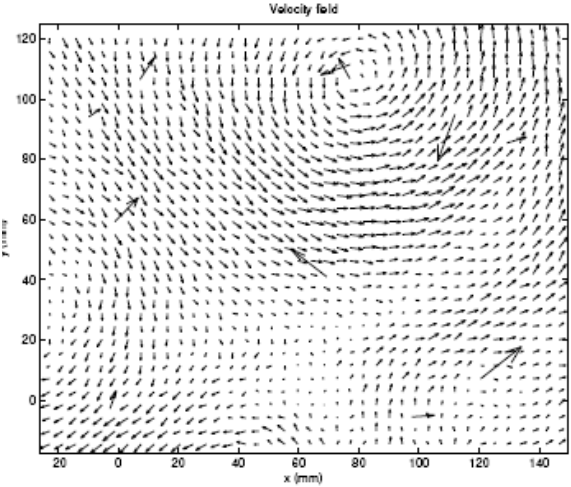
1 cm (1:1)



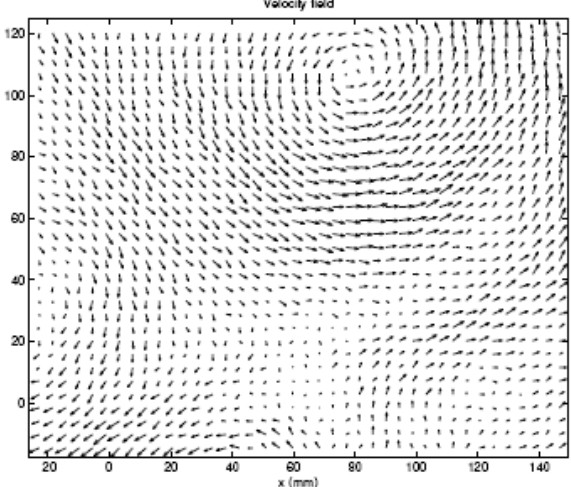
0.5 mm (20:1)



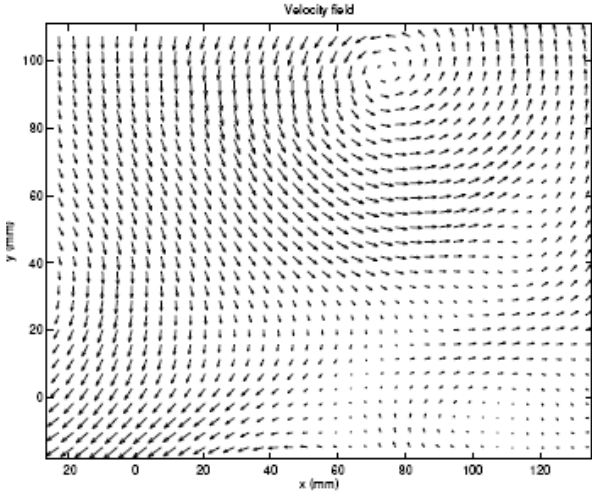
Post-traitement



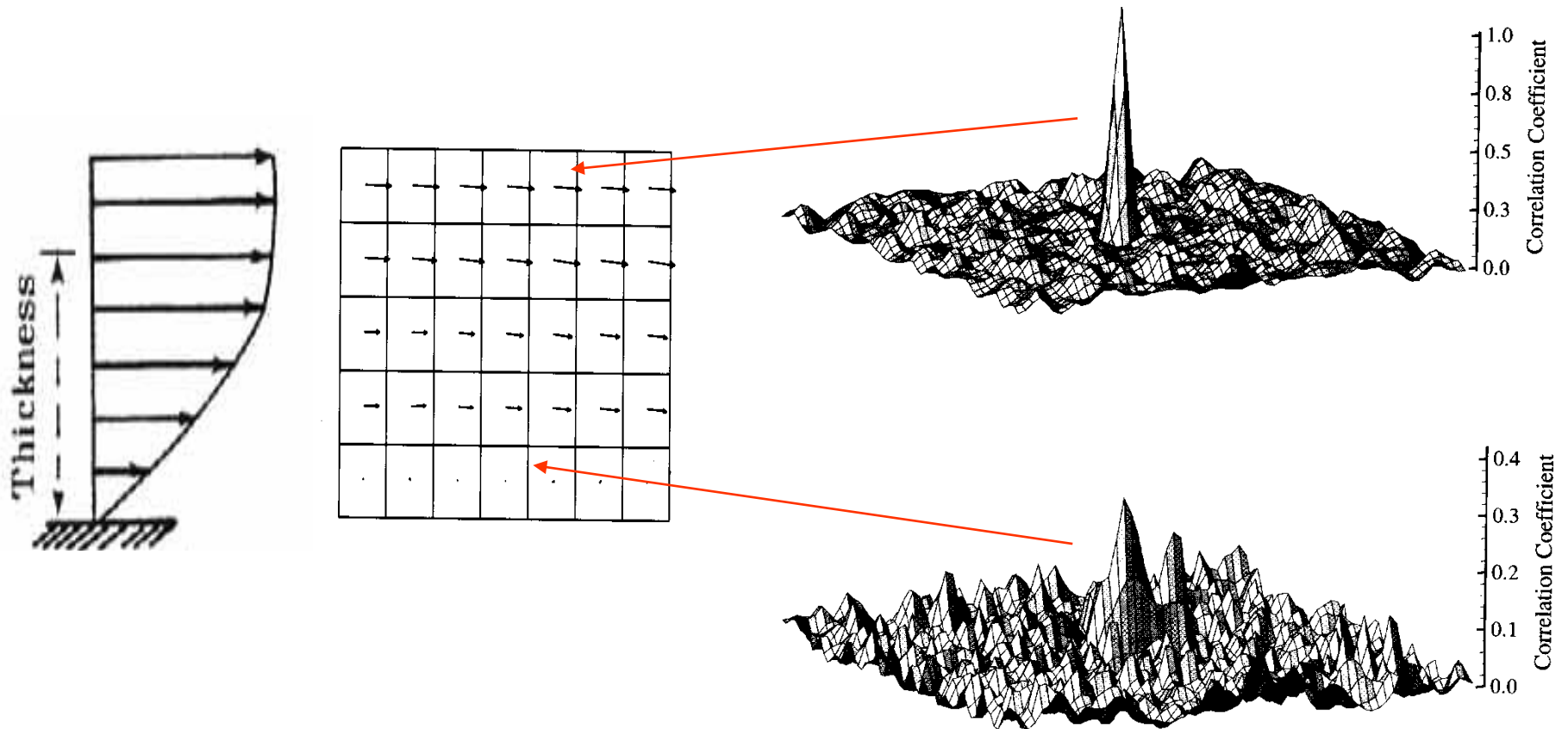
Supression/
Remplacement
Vecteurs
aberrants



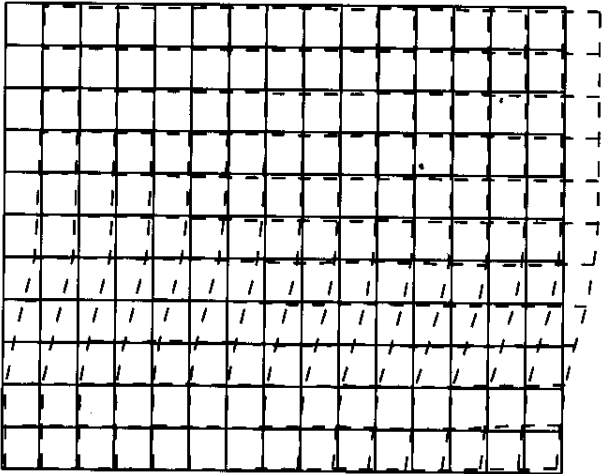
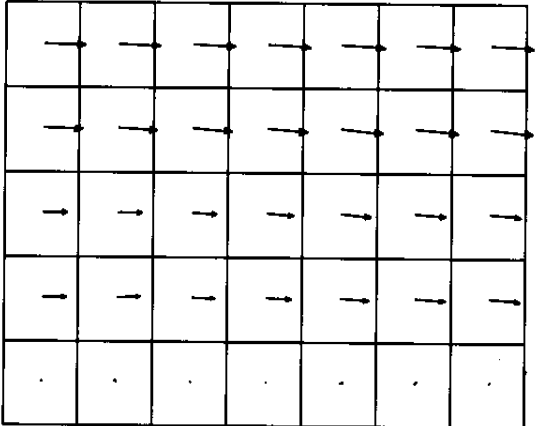
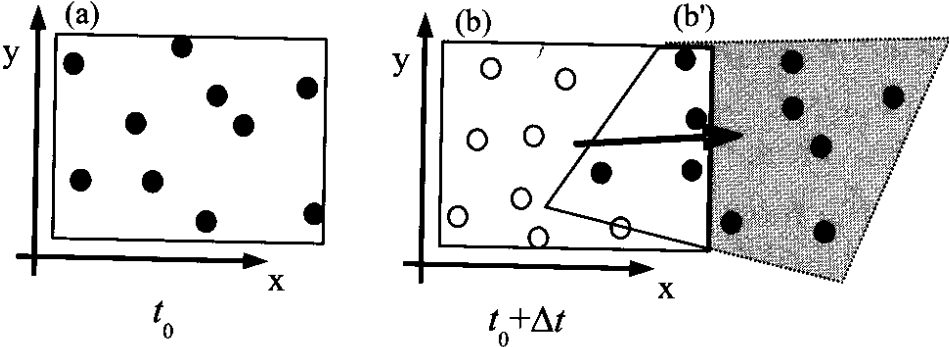
Lissage



Inhomogénéités de vitesse (e.g. cisaillement)



Déformations de fenêtres



PIV : Logiciels commerciaux

(Système d'acquisition + traitement images)

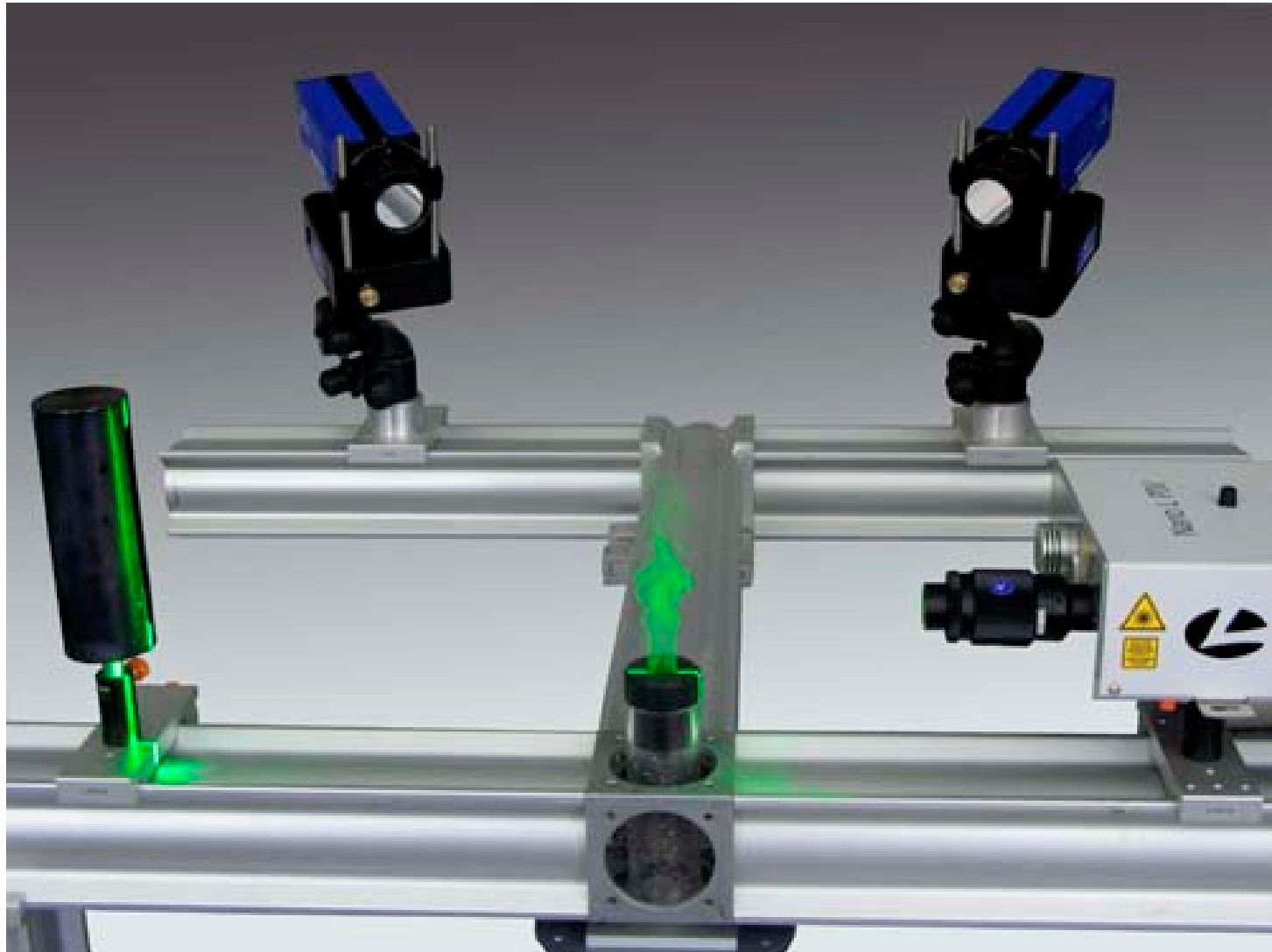


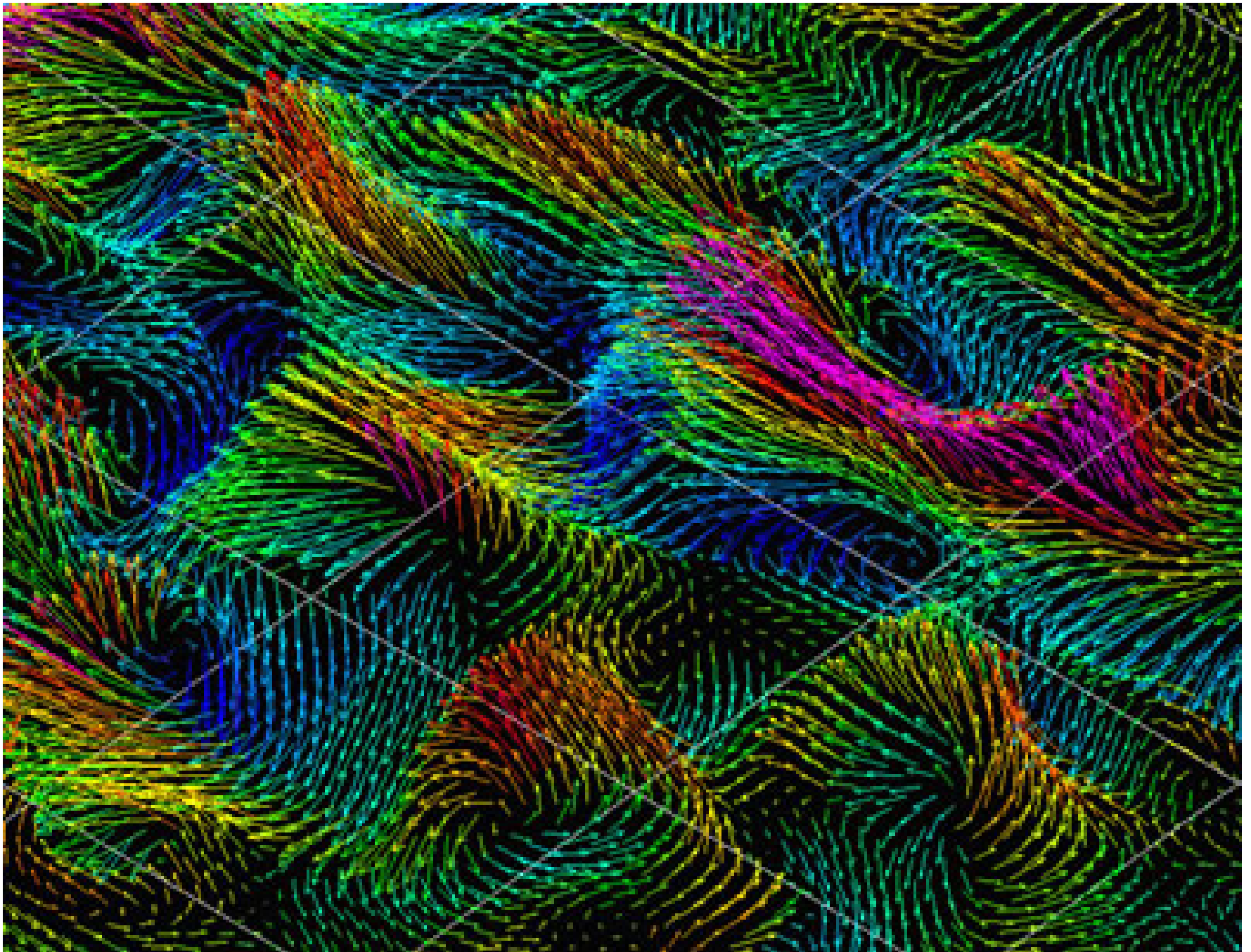
PIV : Logiciels libres

(Traitement images seul)



4 - PIV stéréoscopique (3C2D)





PIV stéréo : principe

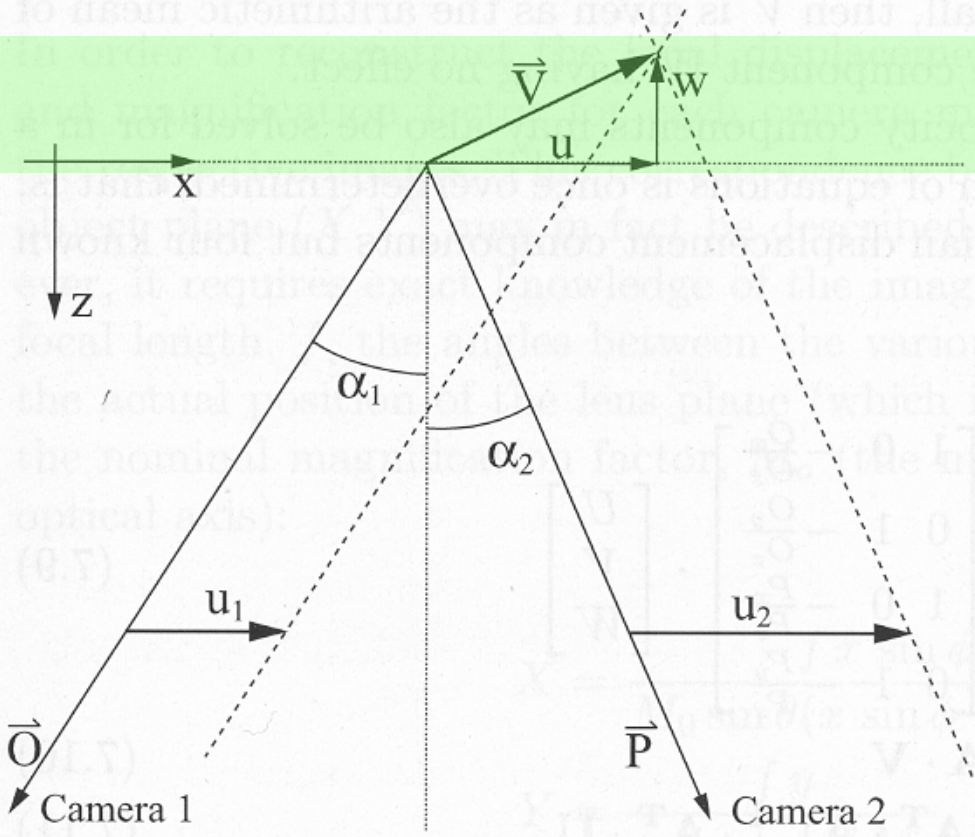
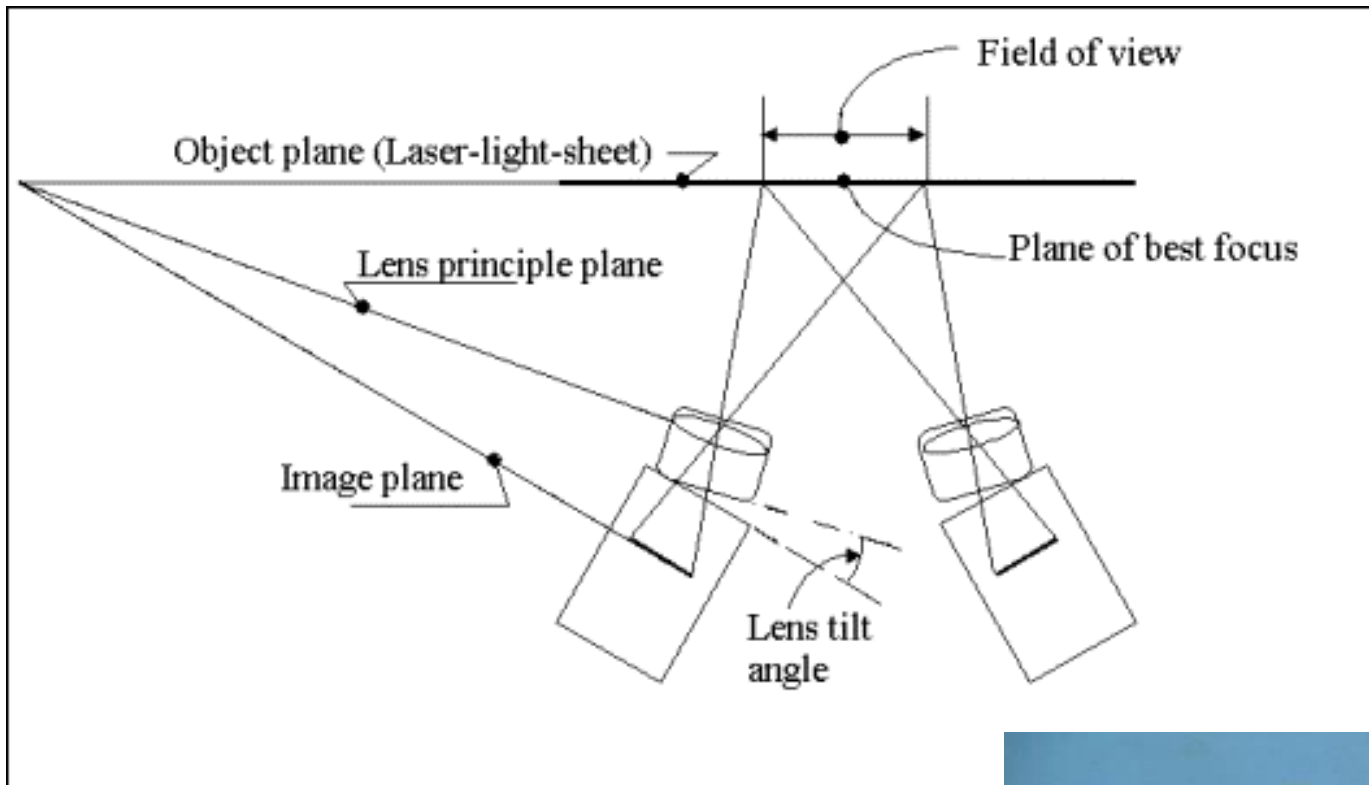
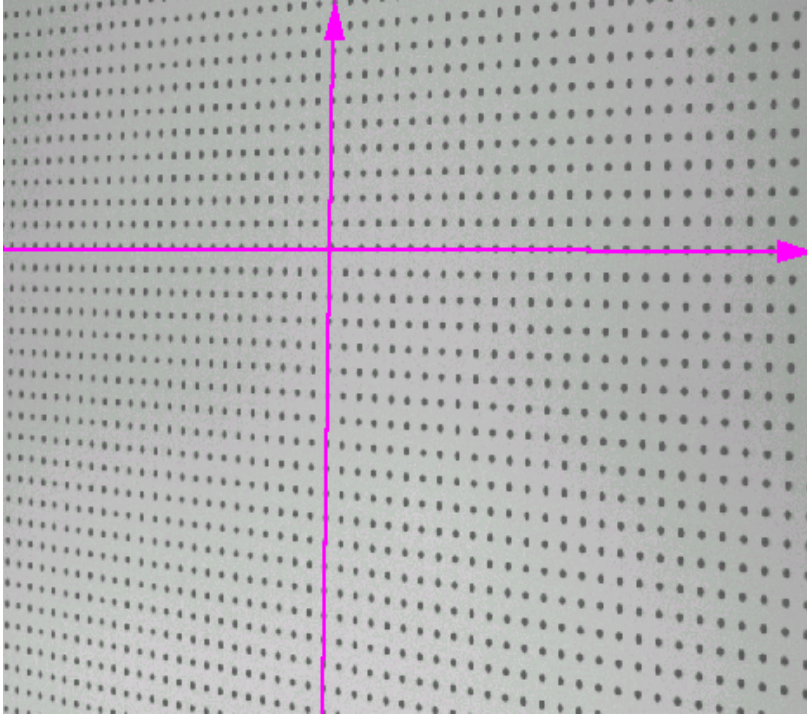
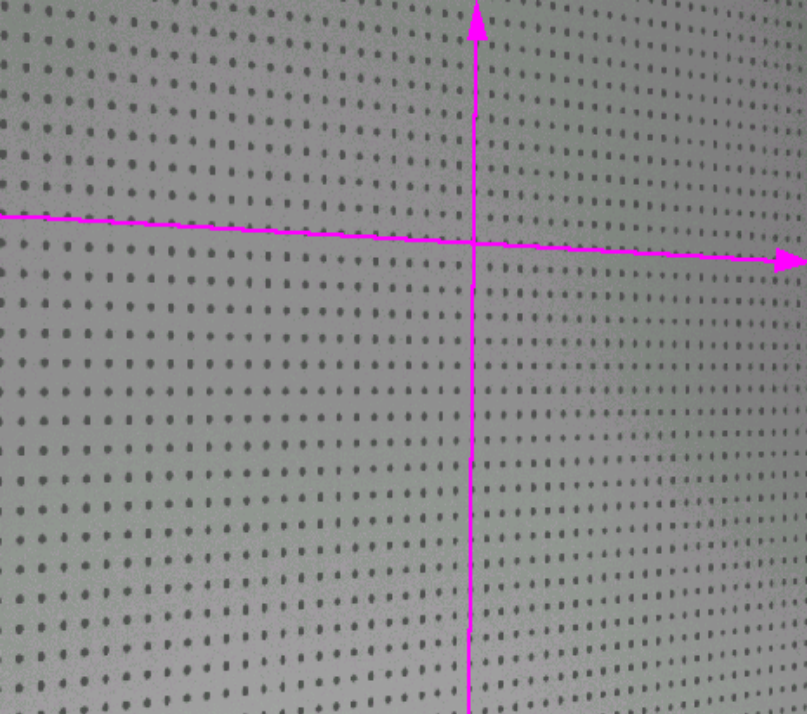


Fig. 7.2. Stereo viewing geometry in the XZ -plane.

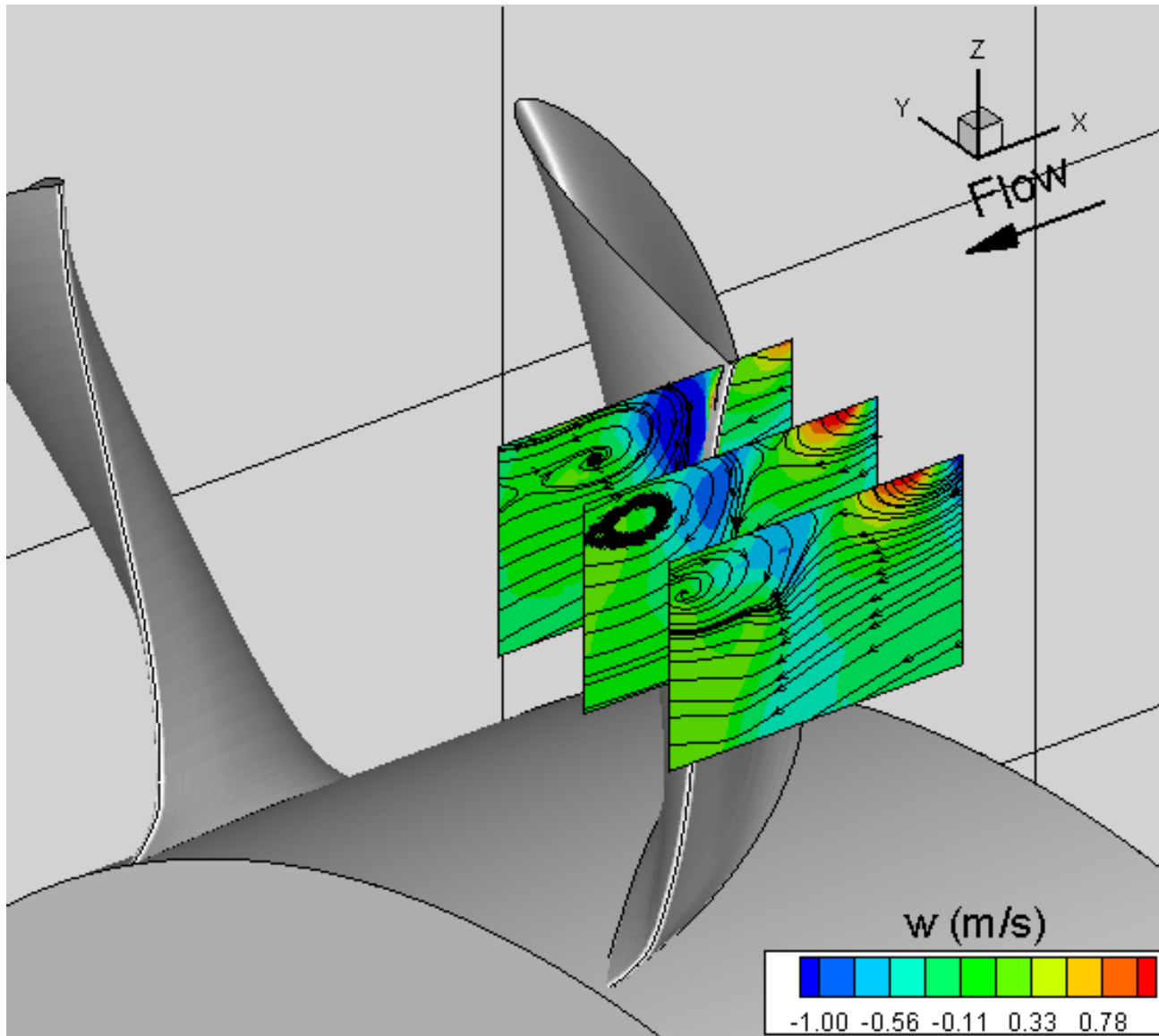
Focalisation : condition de Scheimpflug



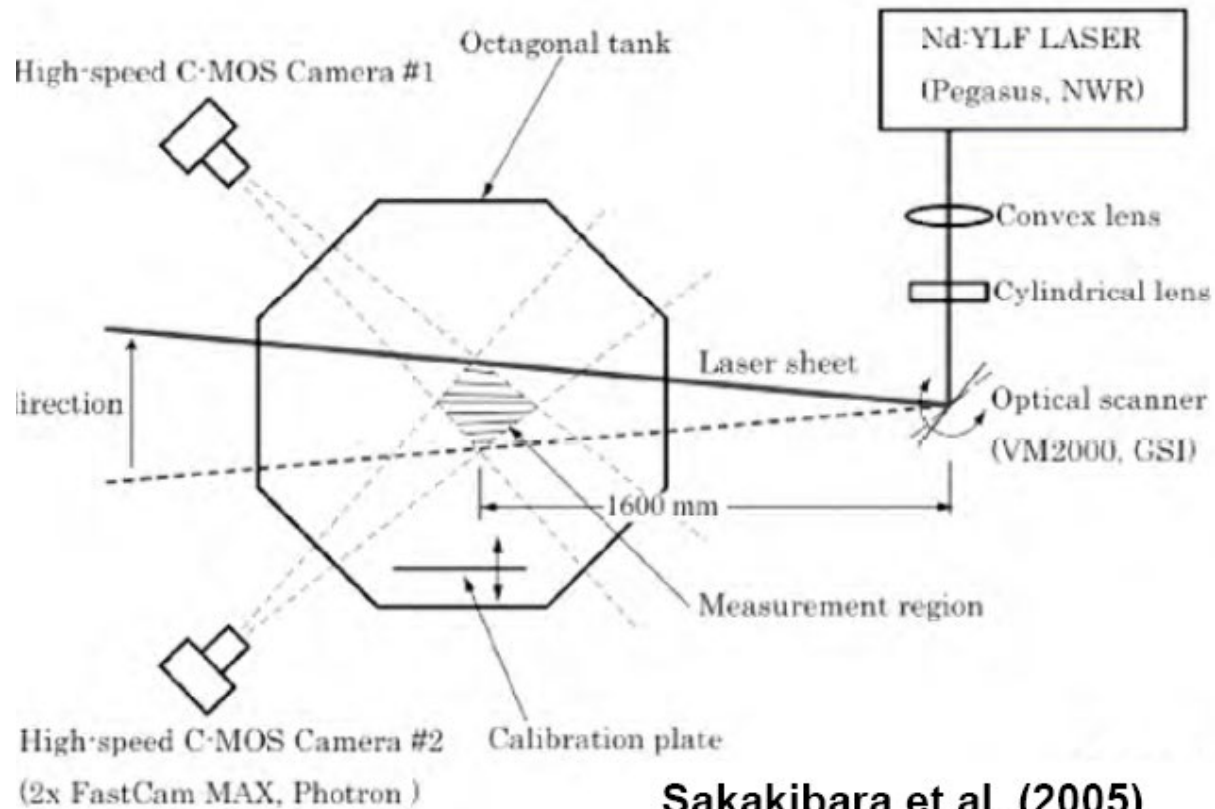
Calibration pour PIV stereo



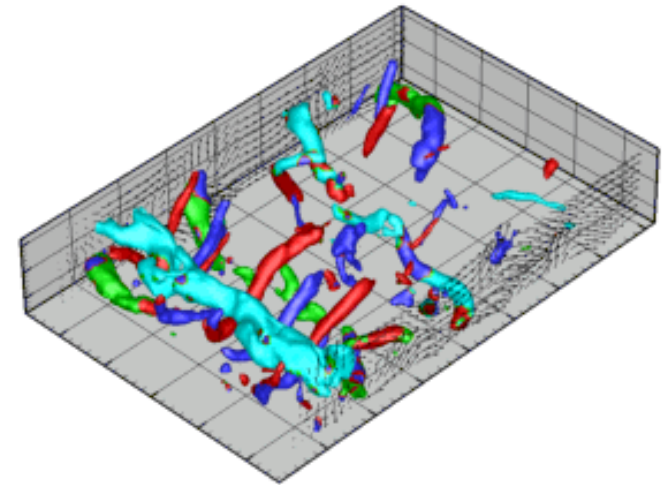
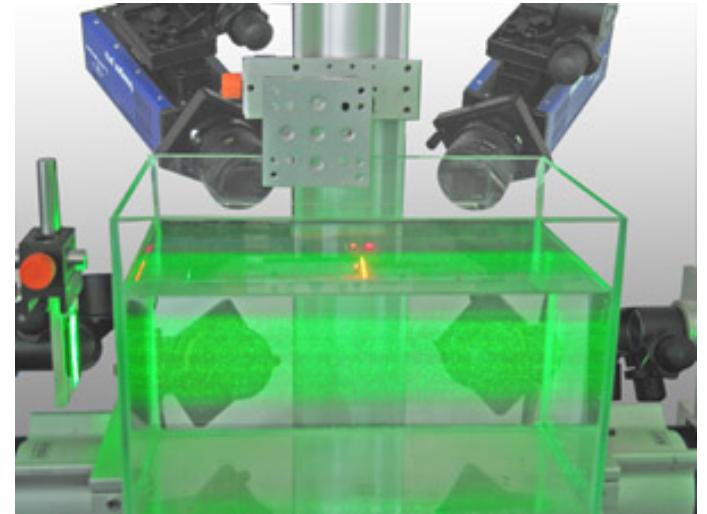
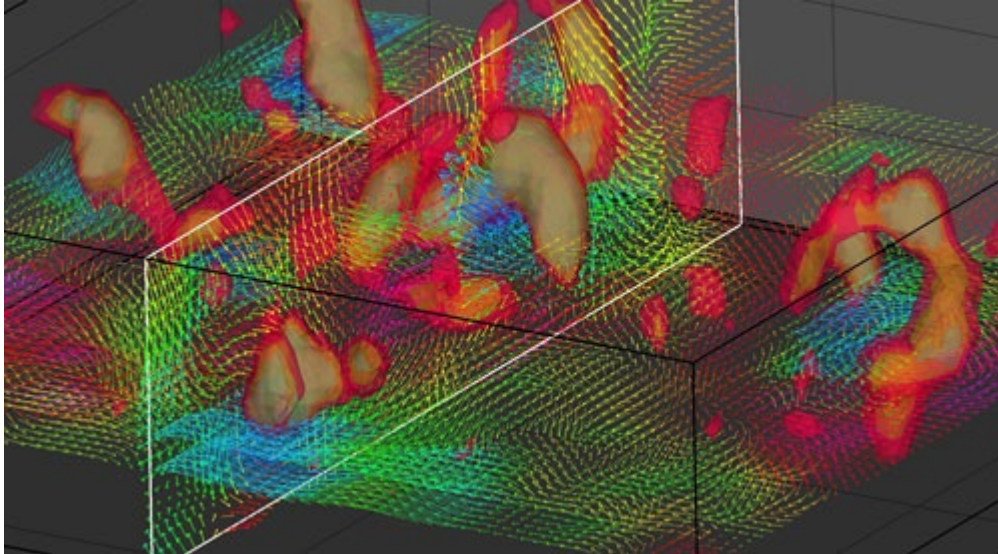
PIV multiplan (3D2C)



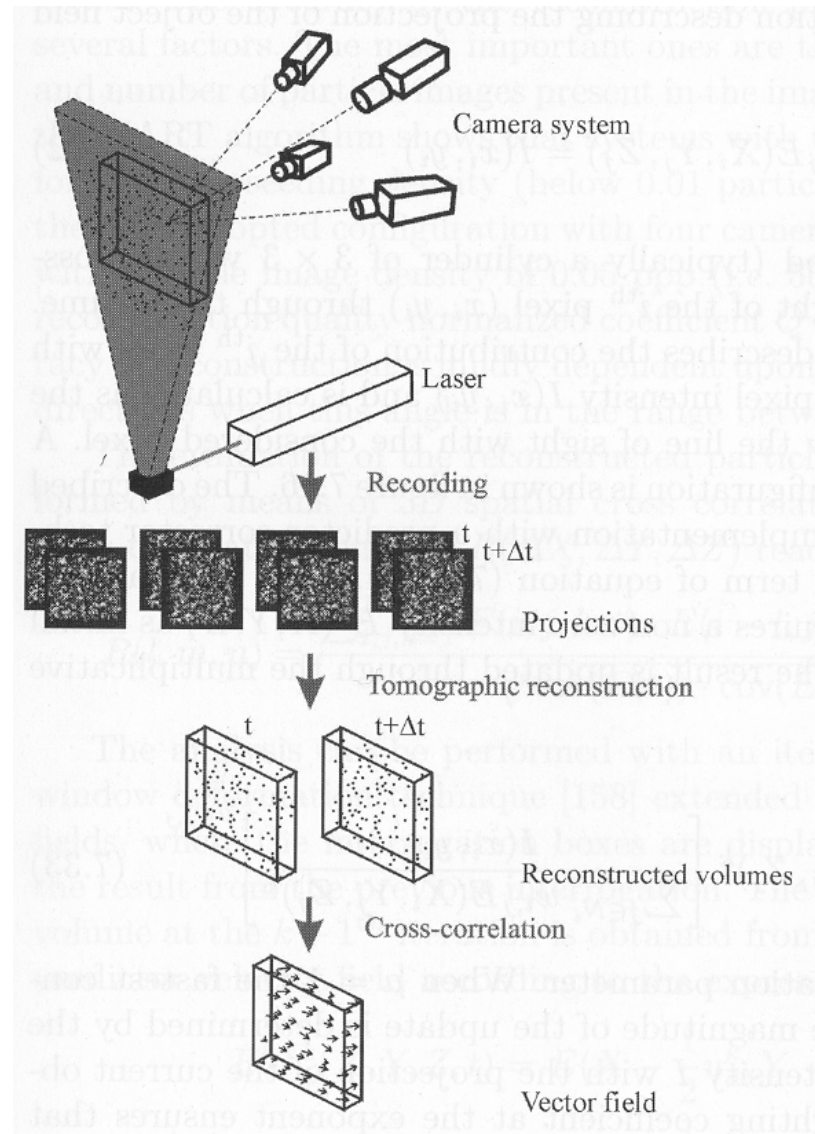
PIV multiplan stéréo par balayage rapide



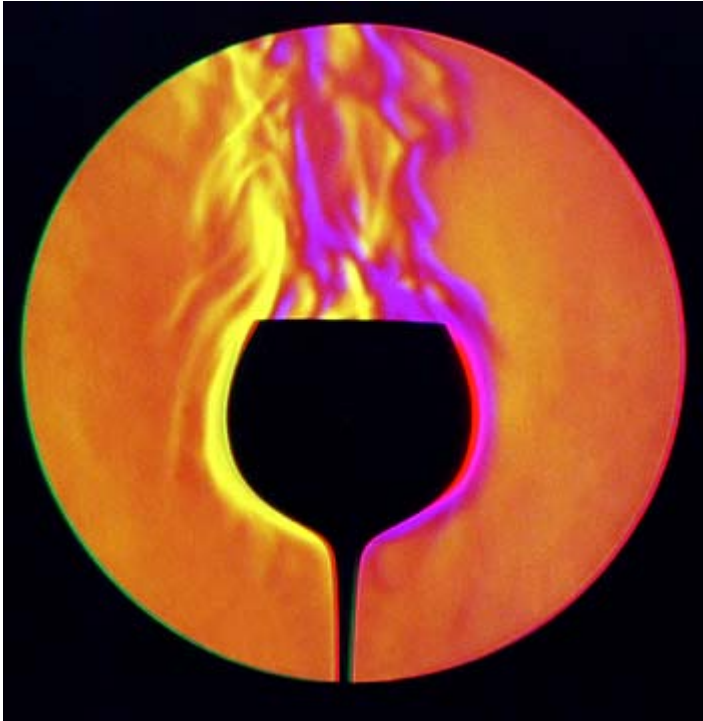
PIV tomographique (3C3D)



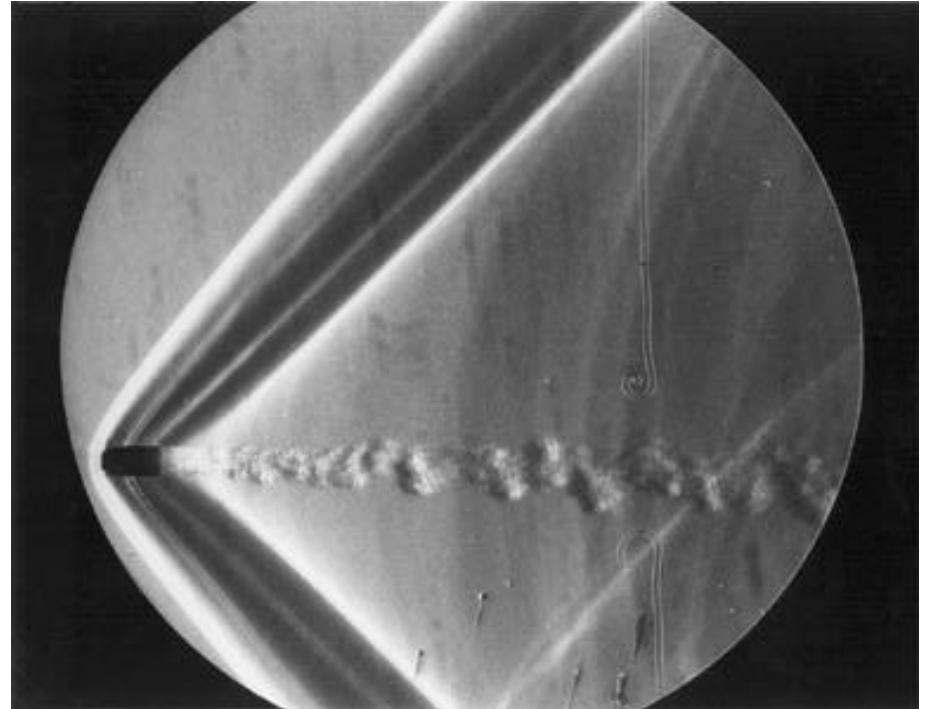
PIV tomographique : Corrélations volumiques



Schlieren (Ombroscopie)

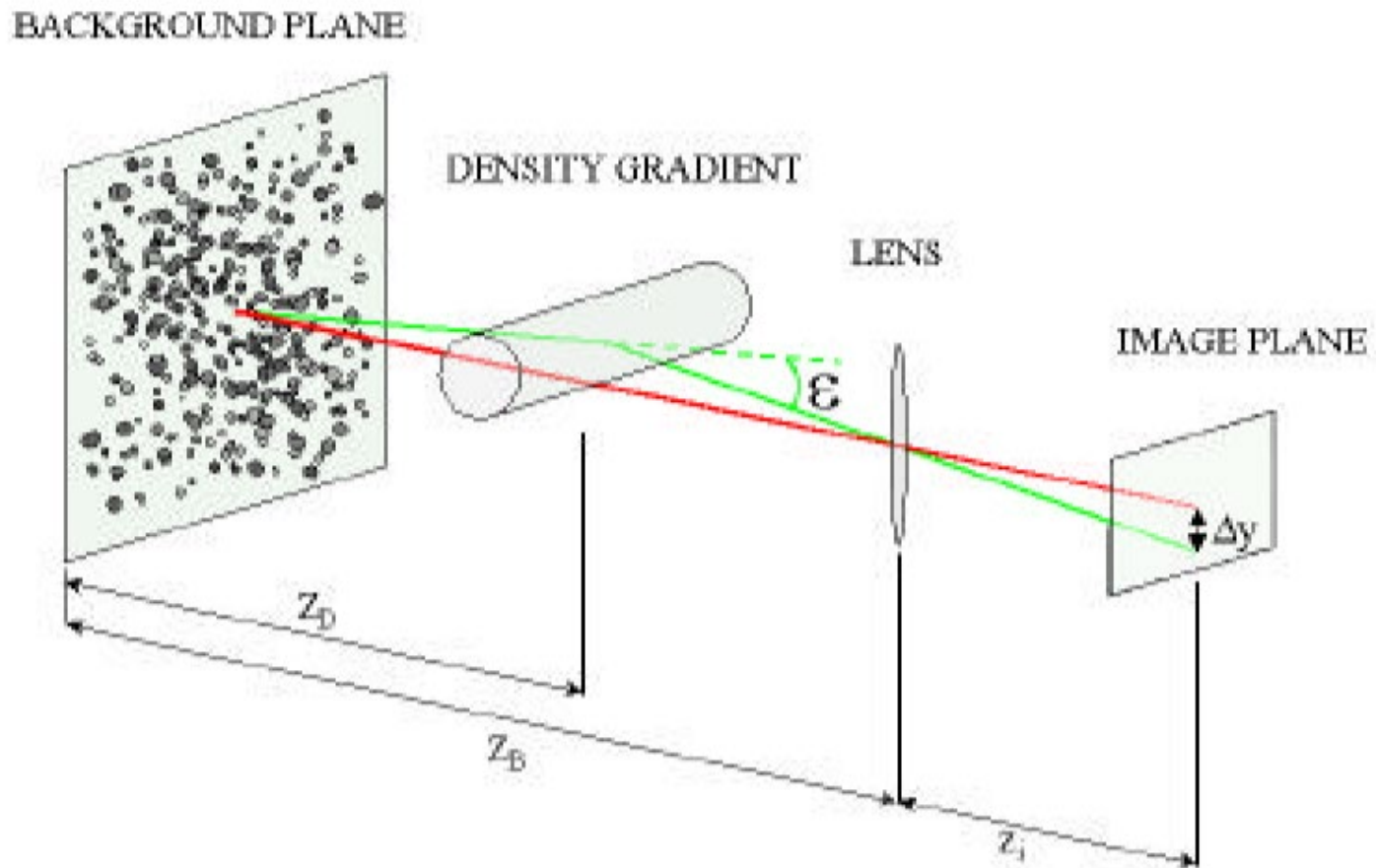


Variations de densité
Induites par température

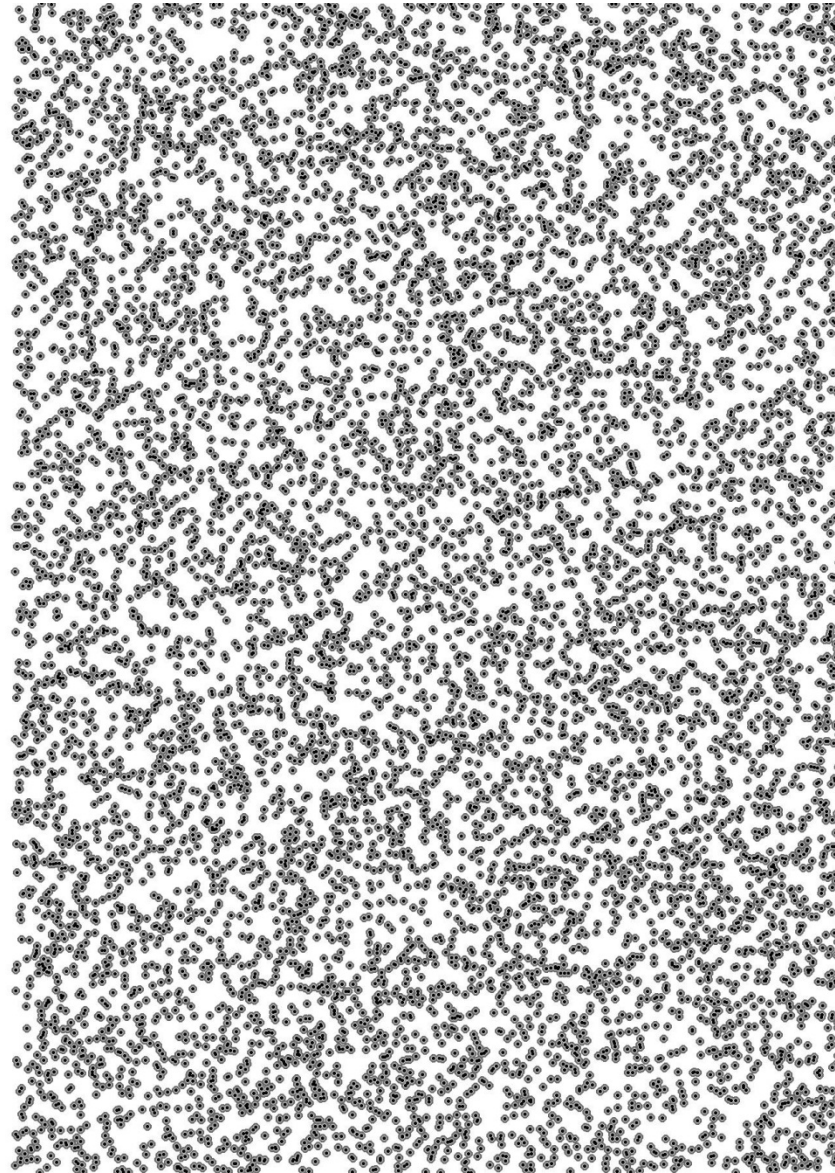


Variations de densité
Induites par effets de compressibilité

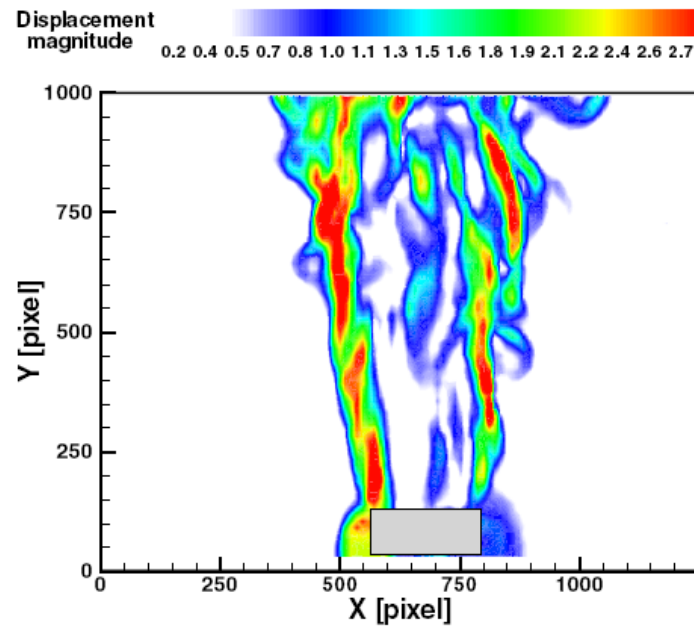
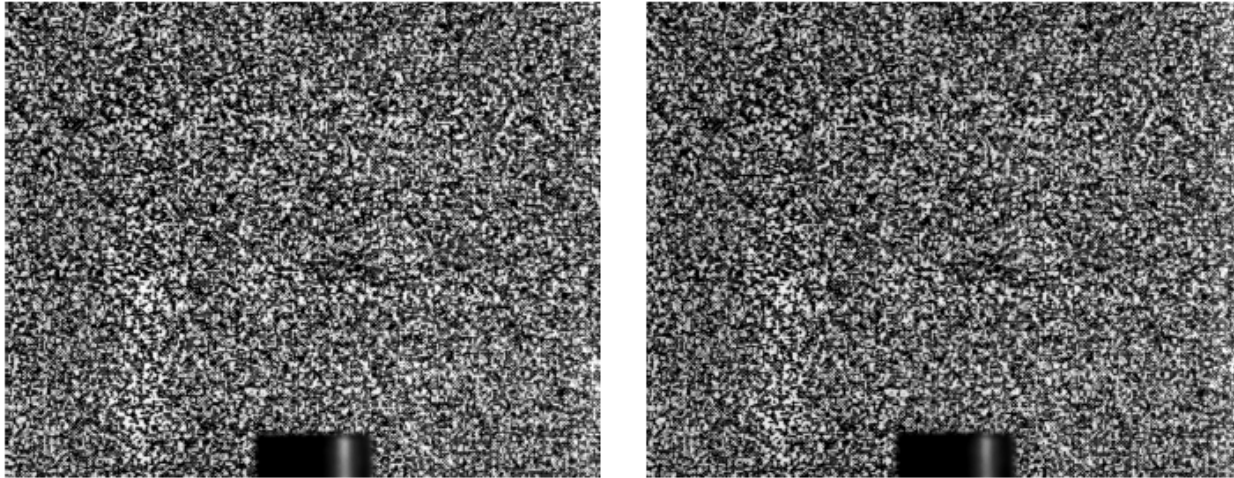
« Synthetic » ou « Background-Oriented » Schlieren



Motif de points aléatoires



Background-Oriented Schlieren : flamme à 1500 °C

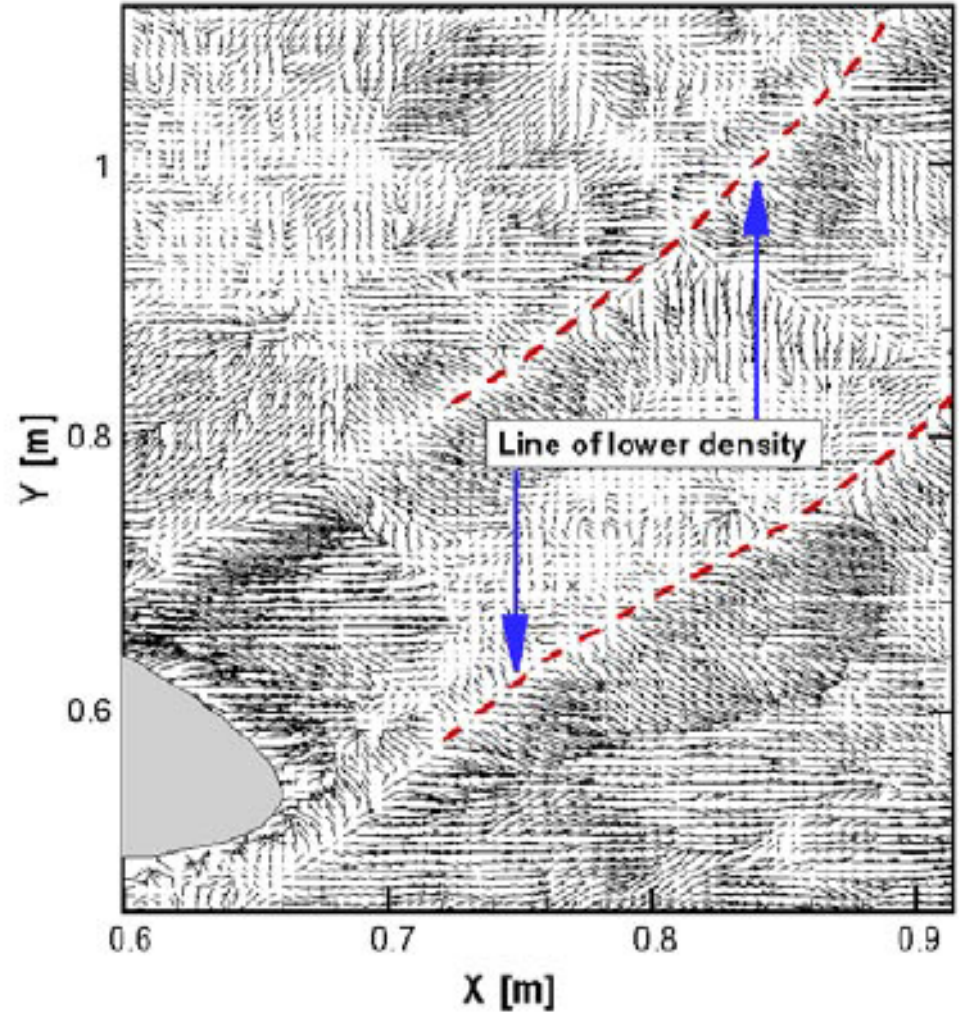


H Richard and M Raffel,
Exp. Fluids (2001)

Background-Oriented Schlieren : Eurocopter BK117



H Richard and M Raffel,
Exp. Fluids (2001)



Sillages : mesures couplées BOS - PIV

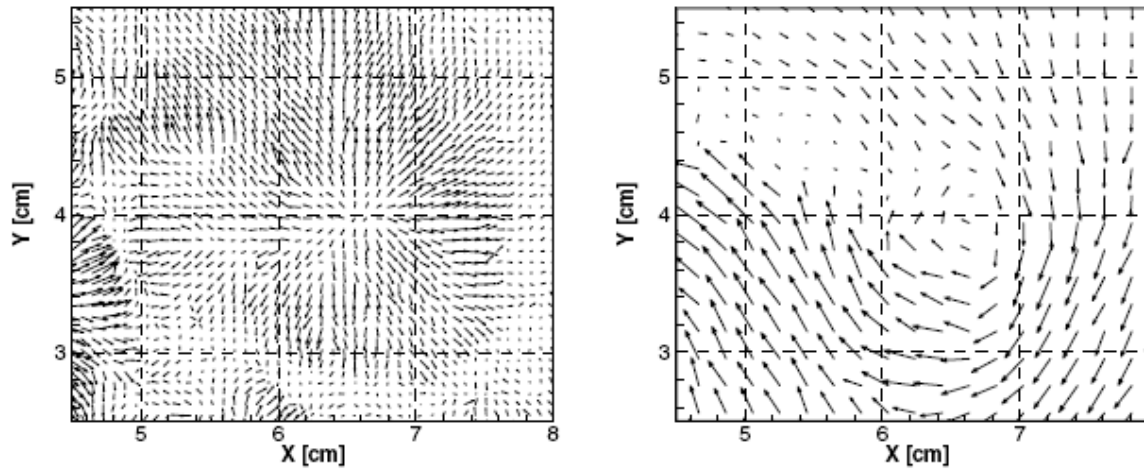


Figure 17. Displacement (left) and velocity (right) fields.

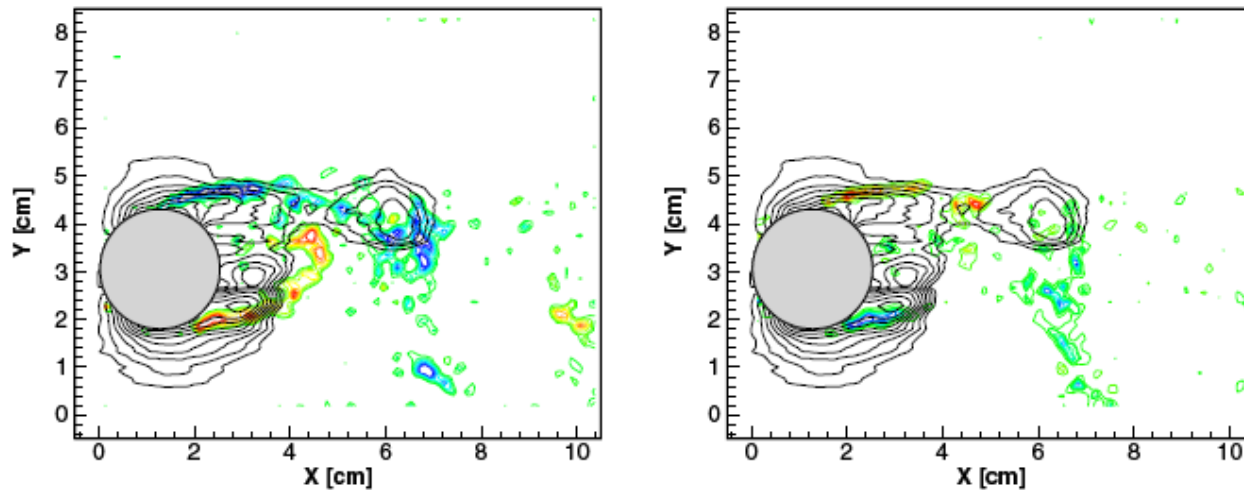
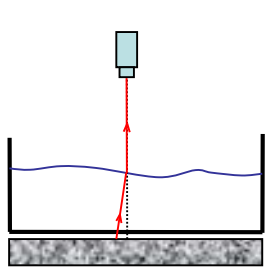
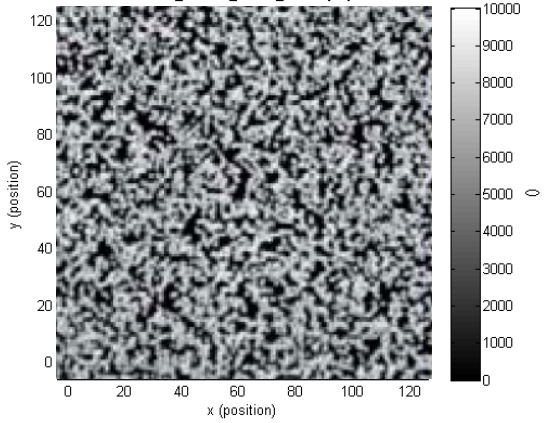


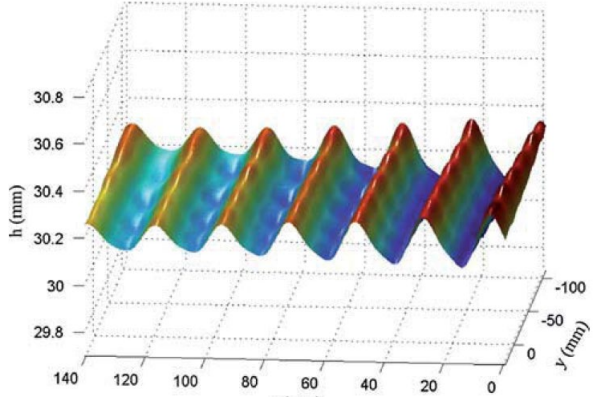
Figure 18. Iso-density lines (black) with iso-vorticity contours (left) and shear strain contours (right).

Free-surface synthetic Schlieren (FS-SS)

Step 1: Images pair (I_0, I_1) of a refracted random dot pattern

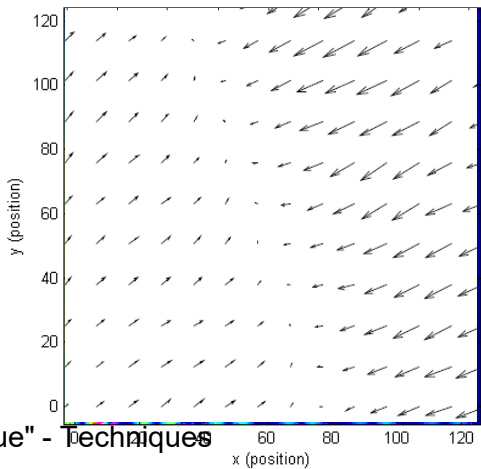


Step 3: Reconstructed topography $h(x,y)$



Digital Image Correlation

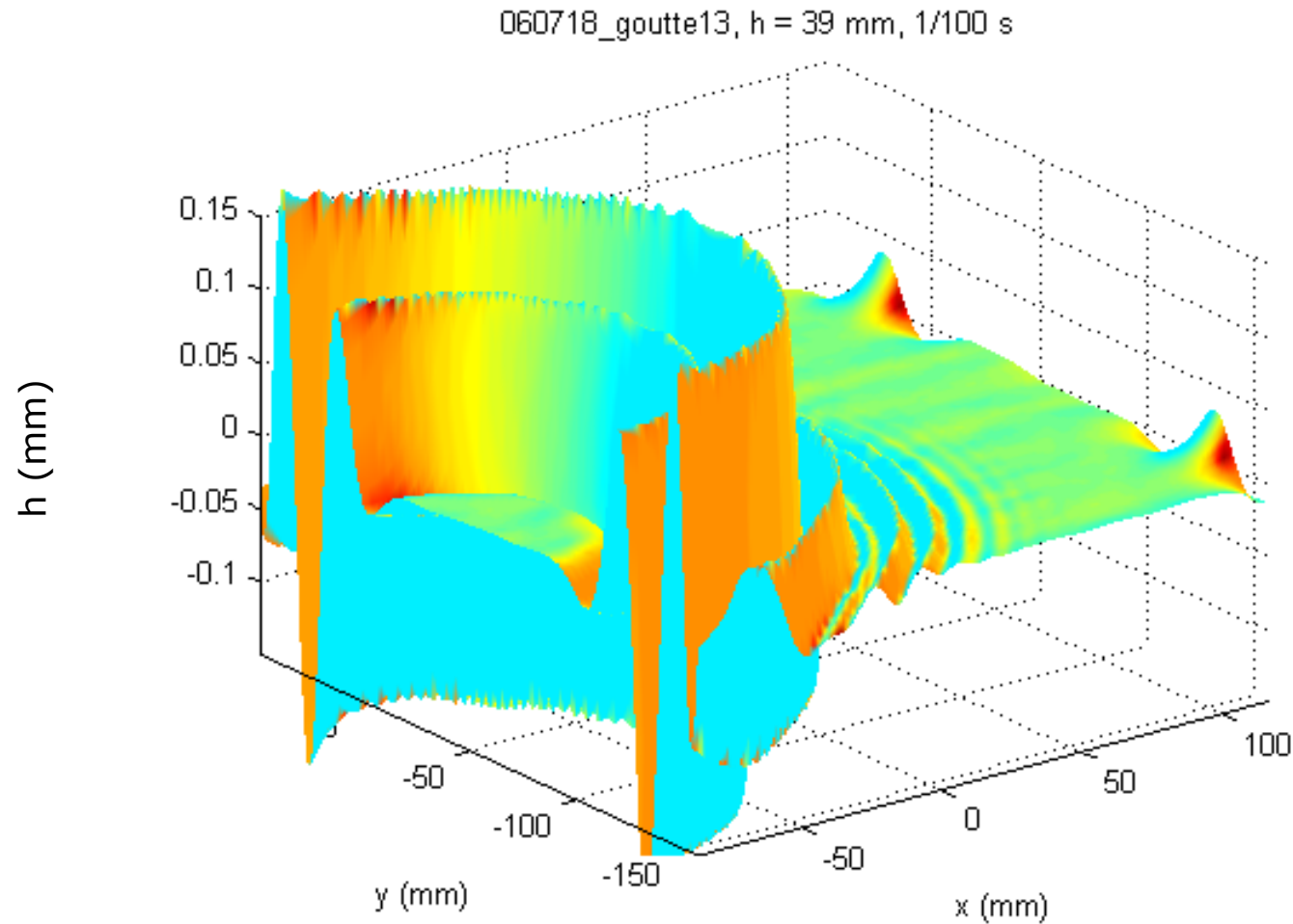
Step 2: displacement field $\delta \mathbf{r}(x, y)$



∇^{-1} using a least-square inversion

Moisy, Rabaud & Salsac, Exp in Fluids (2009)

Wave pattern induced by the impact of a drop (100 Hz)



1 μm capillary ripples detected on a 20x20 cm^2 field