

Plasma-flow : Plasmas et mécanique des fluides

17-20 nov. 2025 Saint-Etienne du Rouvray (France)

La vélocimétrie par images de particules

Bertrand Lecordier (CNRS-CORIA)

Principe de base

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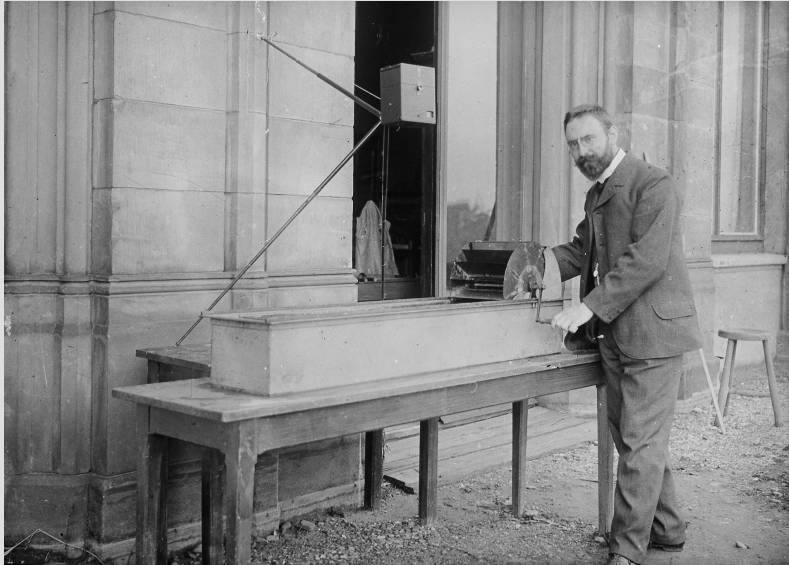
33+(0)2 32 95 36 81

Plan

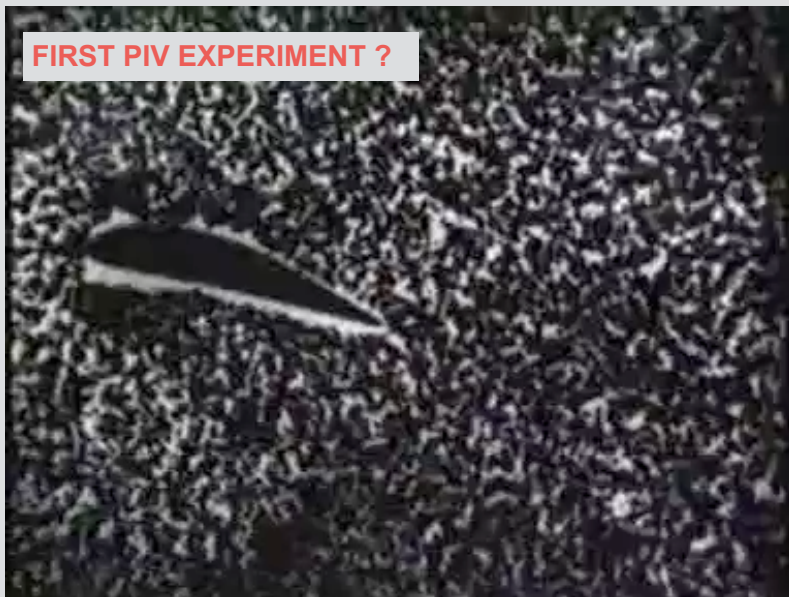
- Introduction
 - Exemples d'application
- Acquisition
 - Sources de lumière
 - Camera
 - Particules d'ensemencement
- Analyse des images de particules
 - PTV / Correlation
 - Estimation des erreurs sur les mesures
 - Bonnes pratiques
- Visite expériences

Introduction

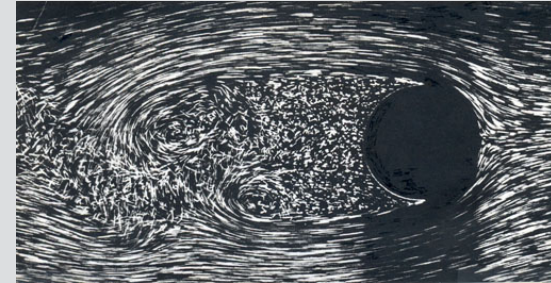
Particle Image Velocimetry : Flow visualisation



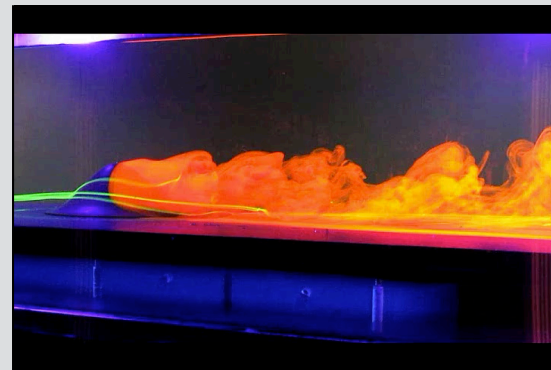
Ludwig Prandtl (1875-1953) in front of his research water channel in Hannover in 1904. The water was propelled with a hand-operated paddlewheel along the 1.5-meter long duct



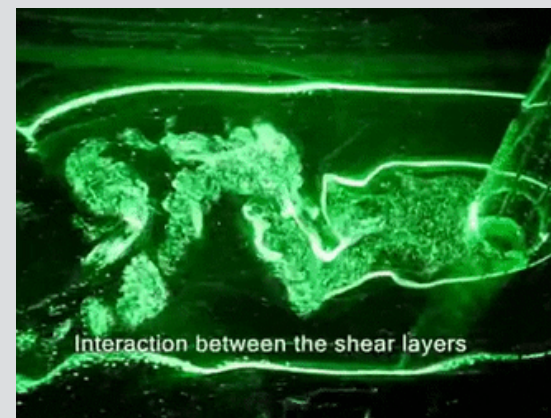
PIV Analysis of Ludwig Prandtl's Historic Flow Visualization Films
Christian Willert, Jürgen Kompenhans



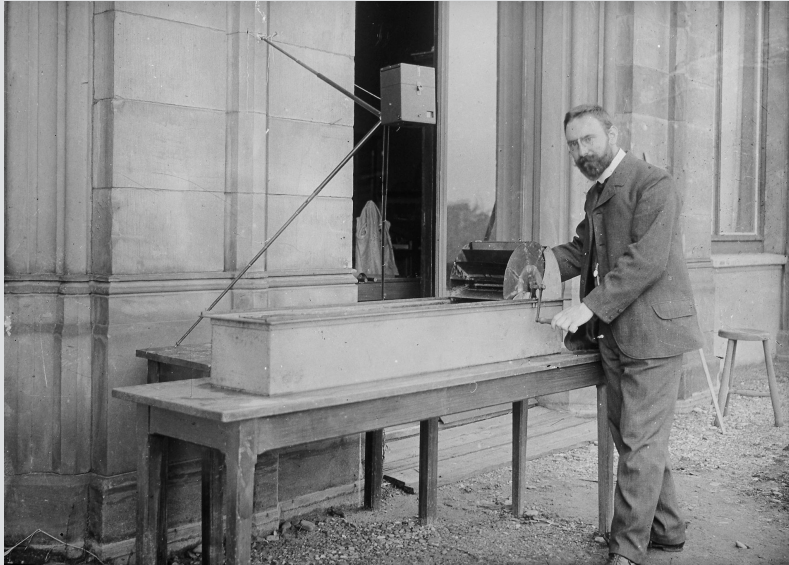
Flow Past a Cylinder at $Re=2000$ [Photograph courtesy Werle and Gallon (ONERA)]



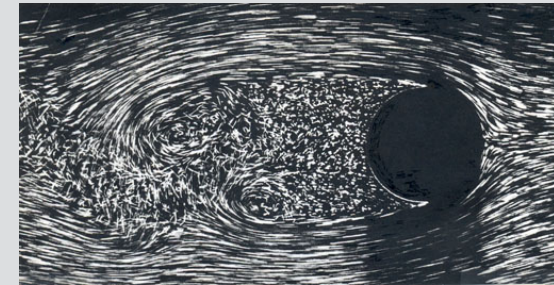
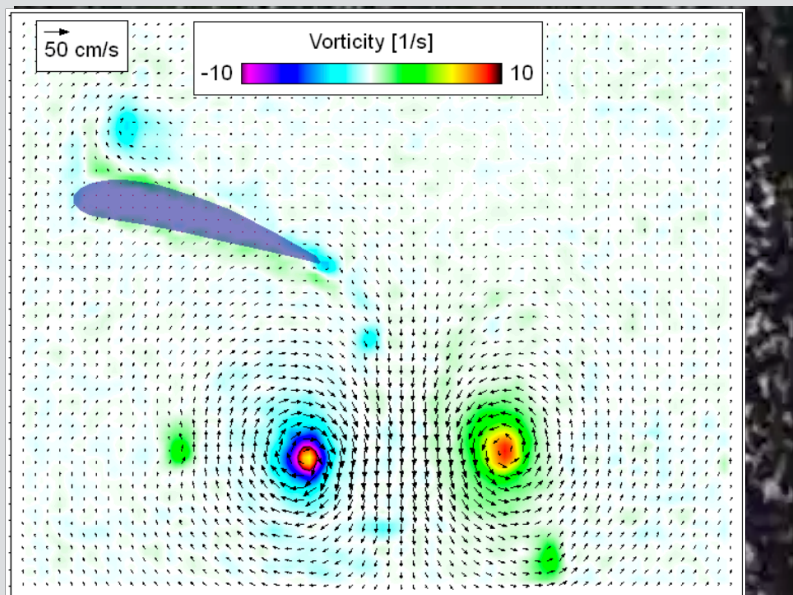
NASA



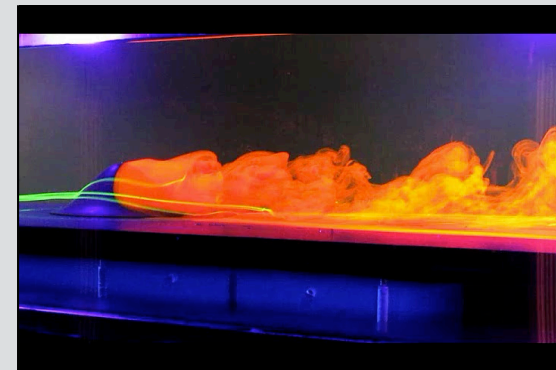
Particle Image Velocimetry : Flow visualisation



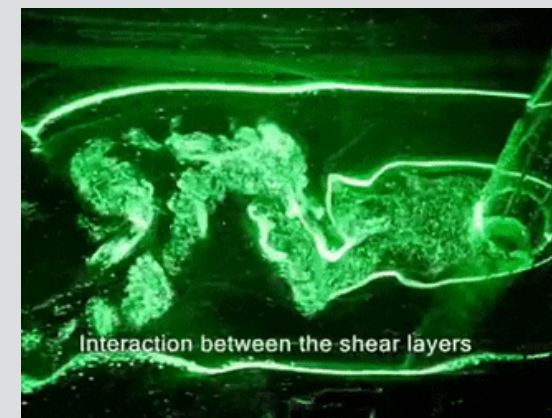
Ludwig Prandtl (1875-1953) in front of his research water channel in Hannover in 1904. The water was propelled with a hand-operated paddlewheel along the 1.5-meter long duct



Flow Past a Cylinder at $Re=2000$ [Photograph courtesy Werle and Gallon (ONERA)]

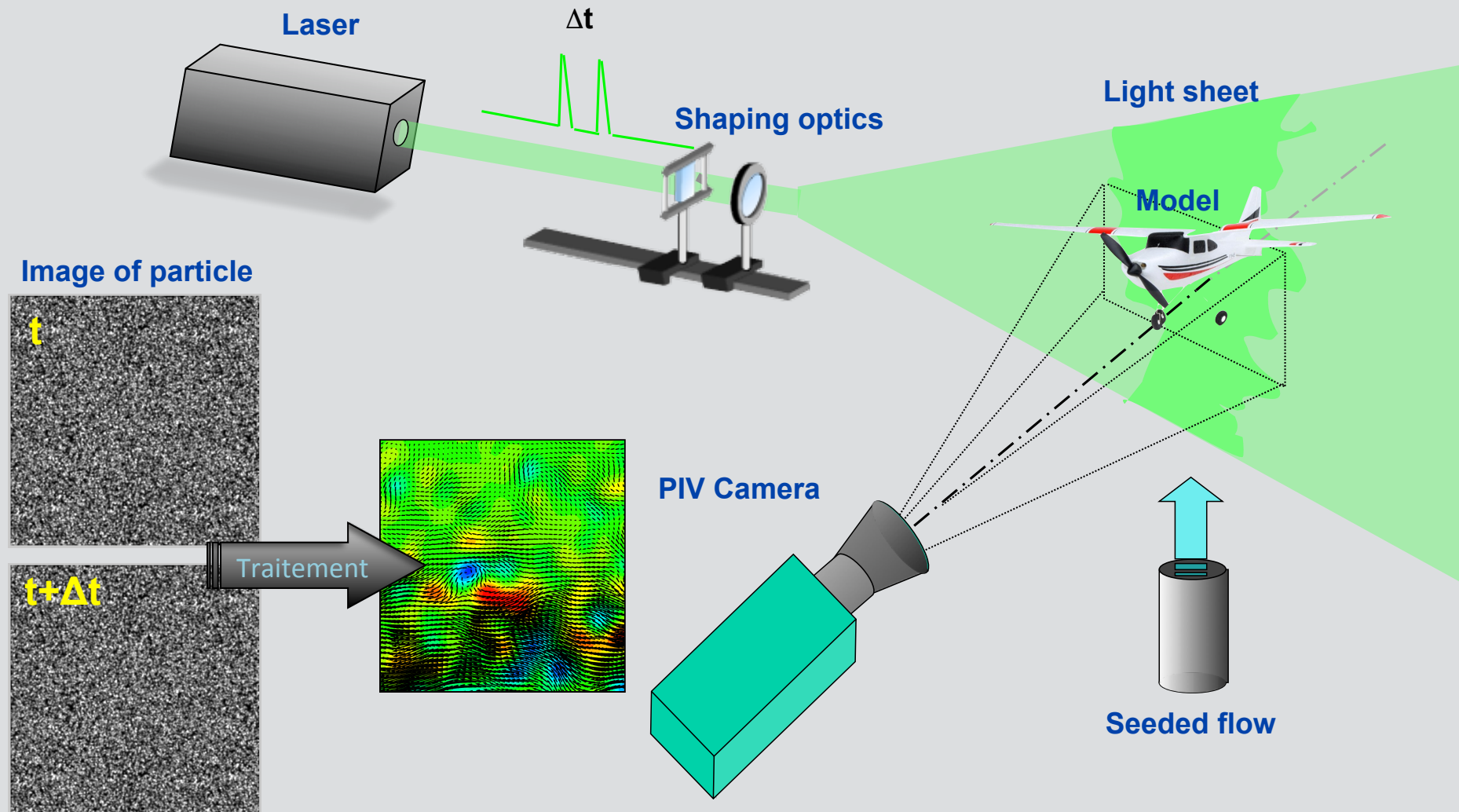


NASA

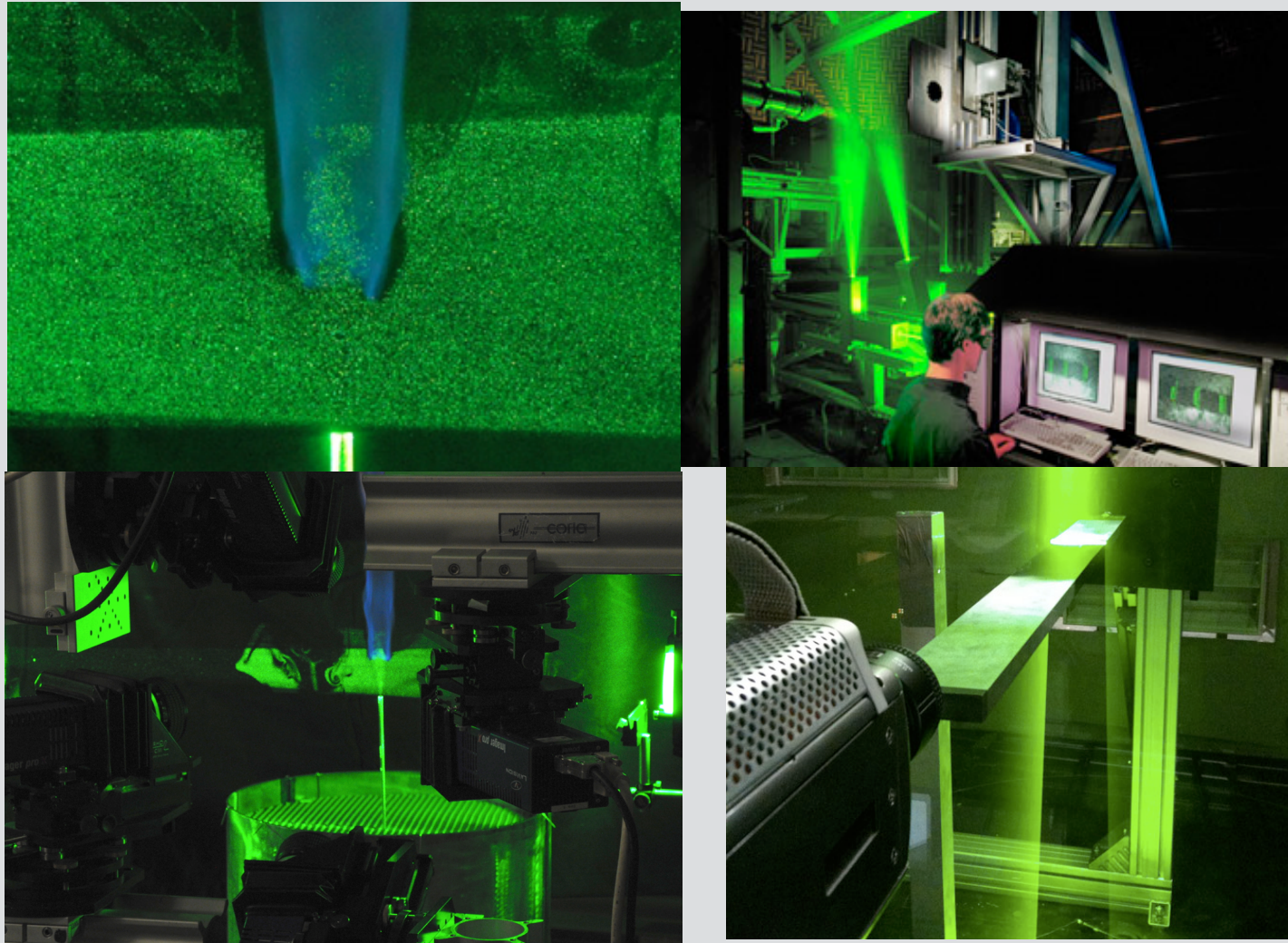


Interaction between the shear layers

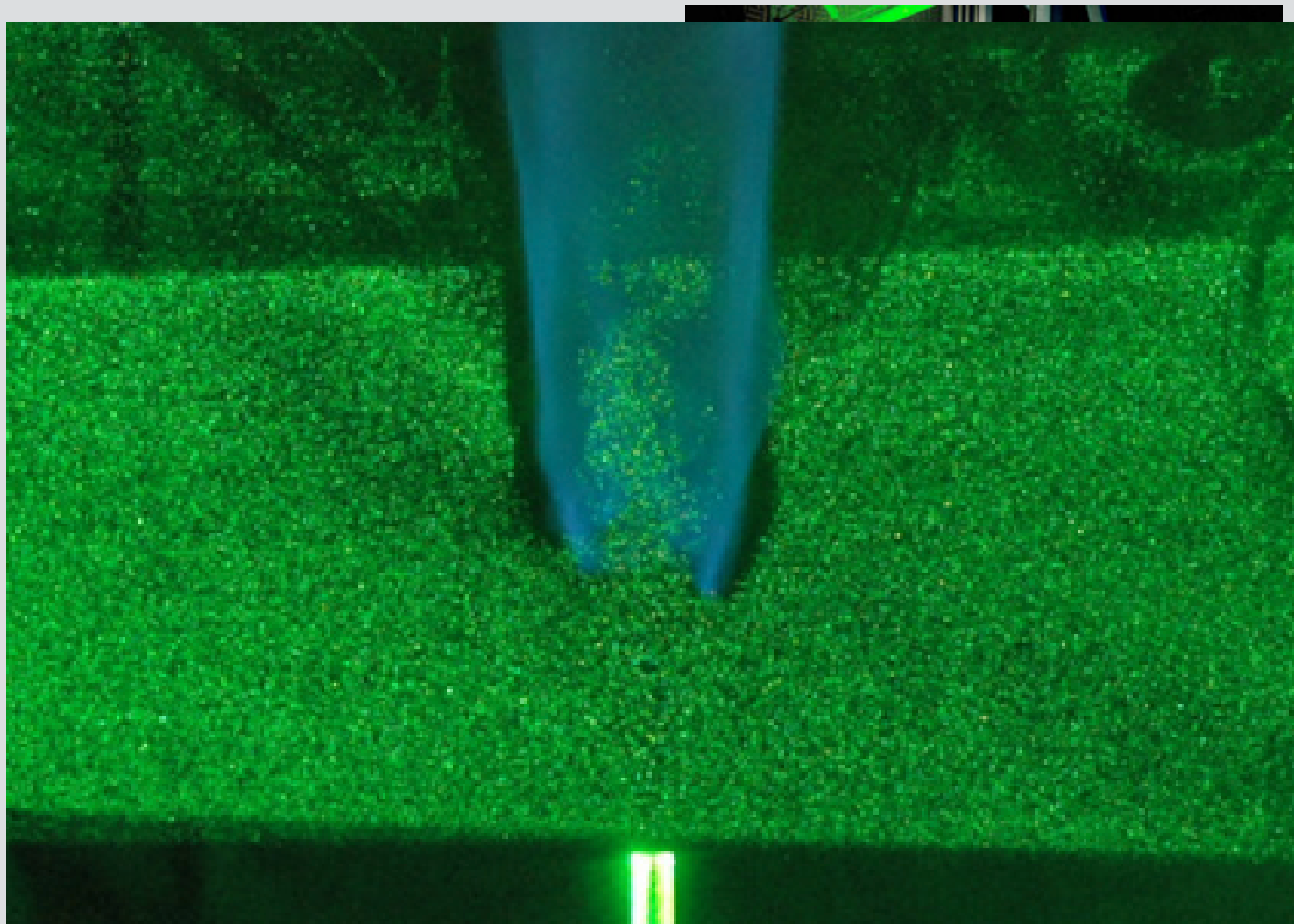
Particle Image Velocimetry : Basic Set-up for PIV recording



Vélocimétrie par images de particules (PIV) - Introduction

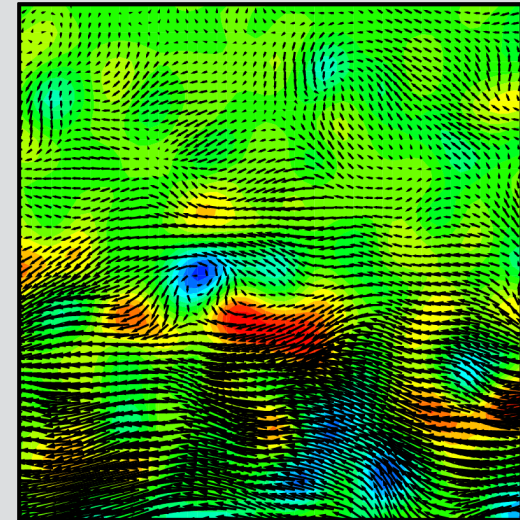
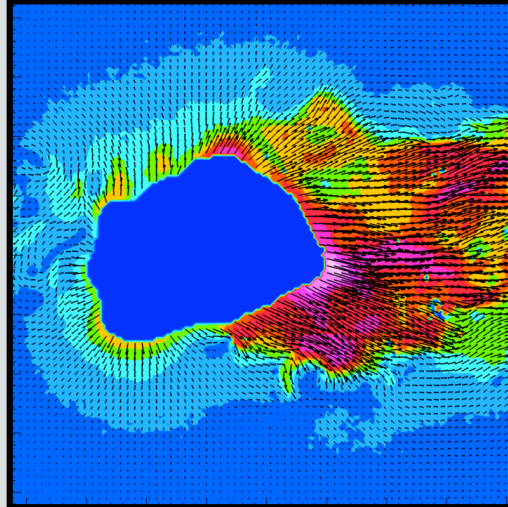
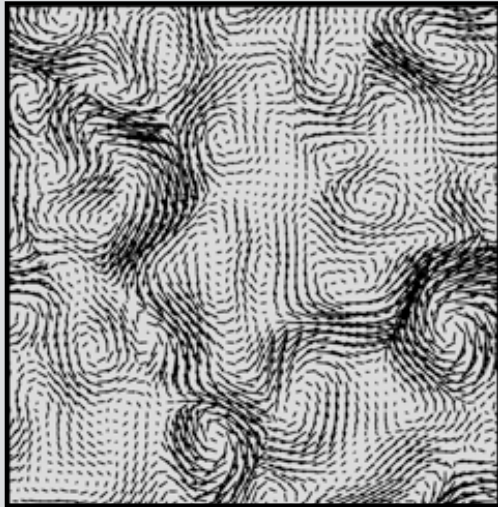


Vélocimétrie par images de particules (PIV) - Introduction



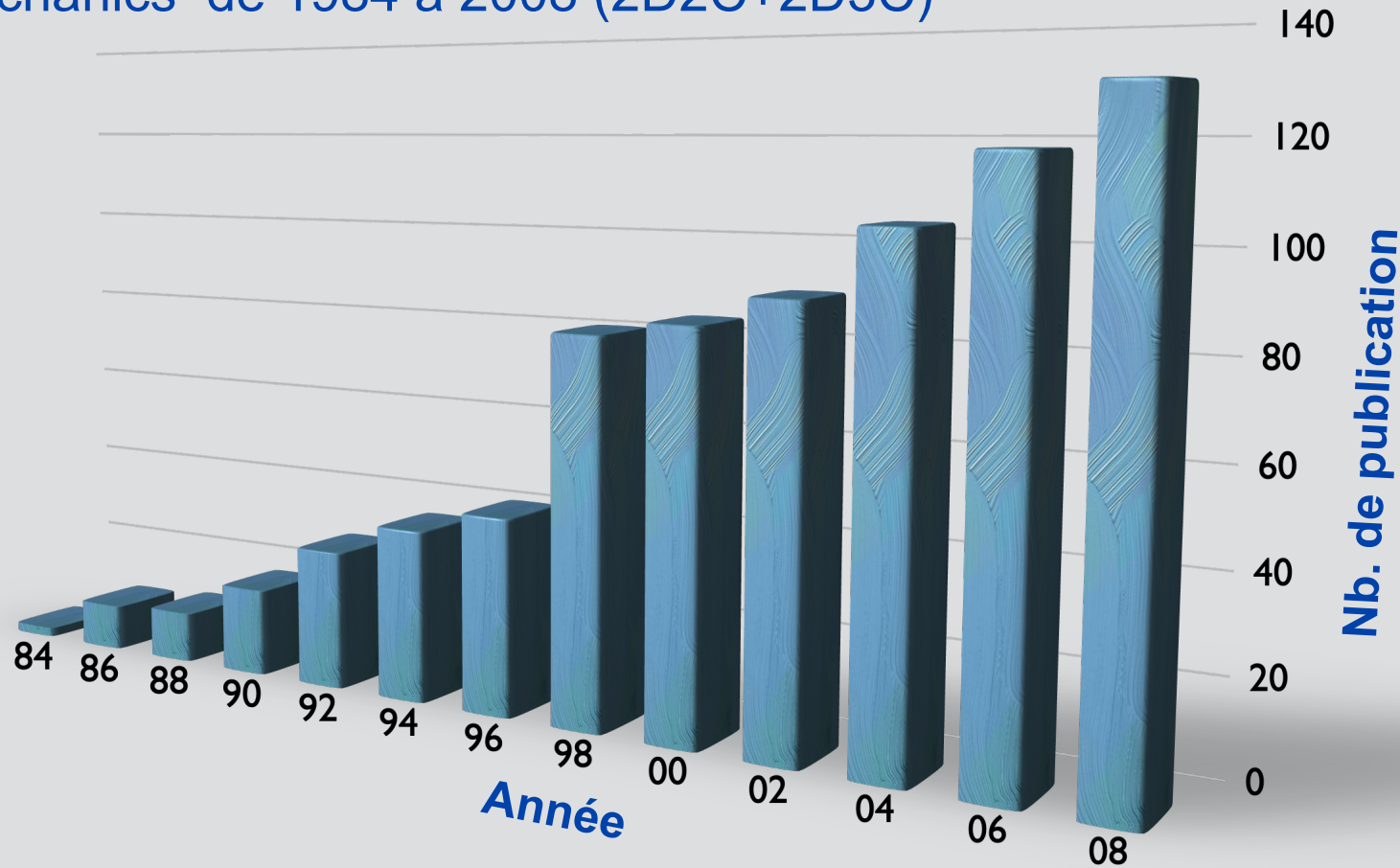
Vélocimétrie par images de particules (PIV) - Introduction

- Champ instantané de vitesse 2D (plan de la nappe laser)
- Echantillonnage temporel : Hz à plusieurs kHz
- Champ d'étude : du μm à 2 m
- Composantes de vitesse : 2 dans le plan - (2D2C)
 - Extension à 3 composantes dans le plan – Stéréoscopie (2D3C)
 - Extension à 3 composantes en volume (3D3C)



Vélocimétrie par images de particules (PIV) - Introduction

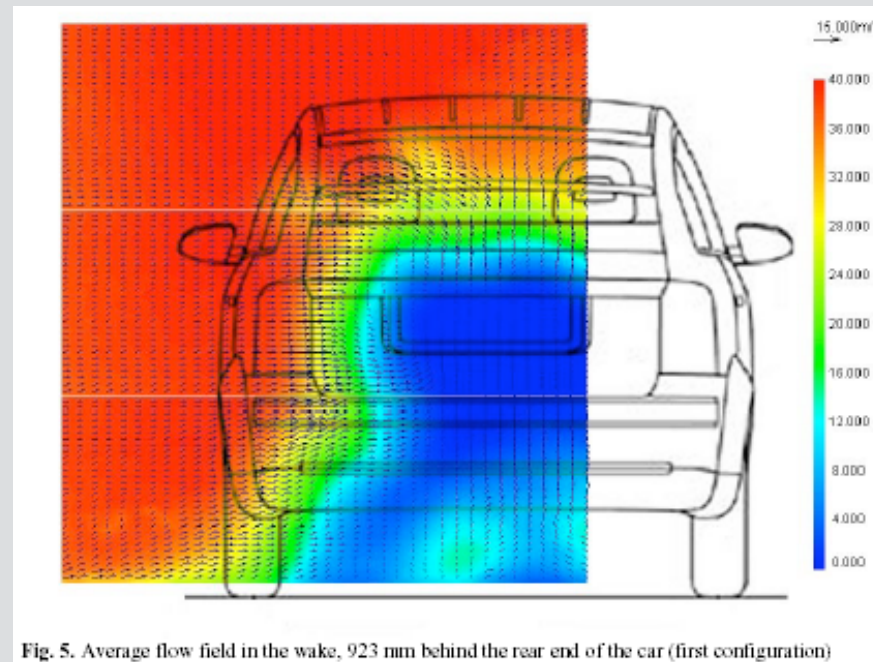
- Nombre de communication développant ou utilisant la PIV à l'International Symposium on Applications of Laser Techniques to Fluid Mechanics de 1984 à 2008 (2D2C+2D3C)



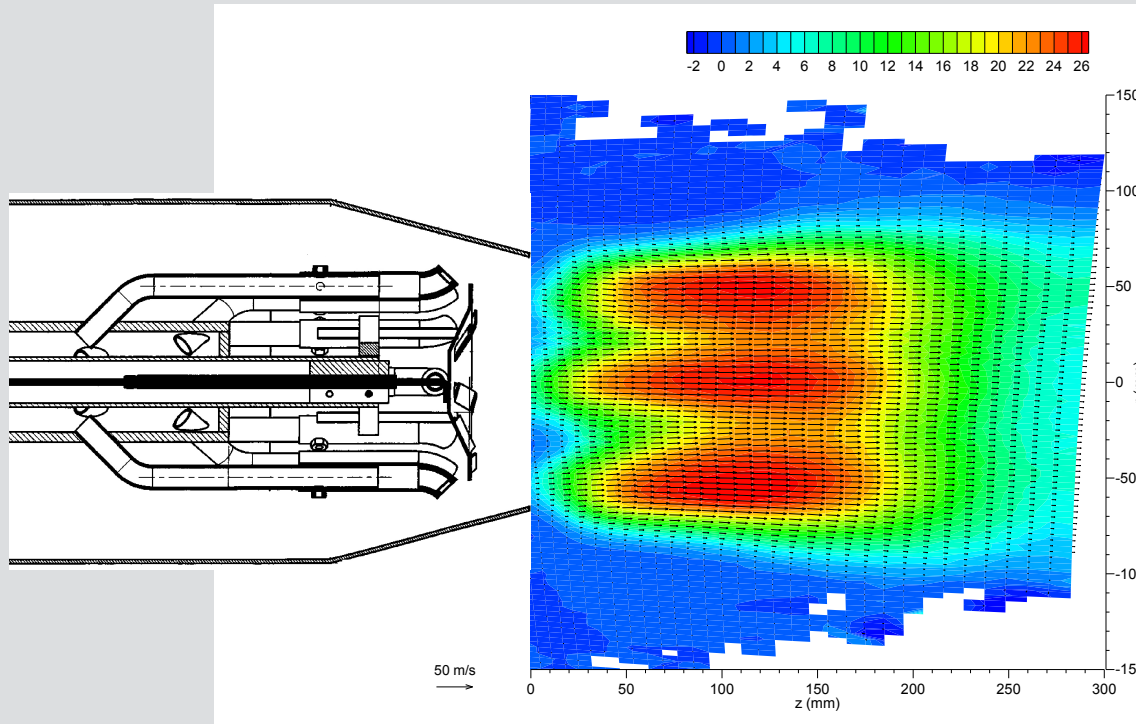
Applications

Vélocimétrie par images de particules (PIV) - Applications

Exemple de champ de vitesse obtenu par PIV dans le sillage d'une automobile à l'échelle 1 dans la soufflerie Audi (Wendt & Fürll, 2001).

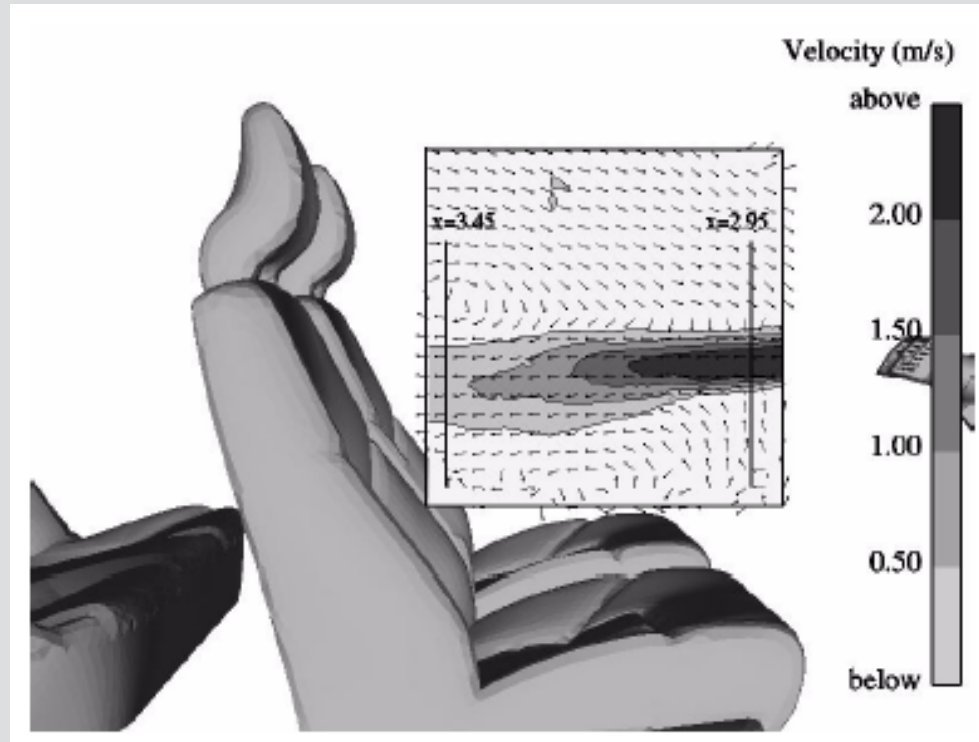


Vélocimétrie par images de particules (PIV) - Applications



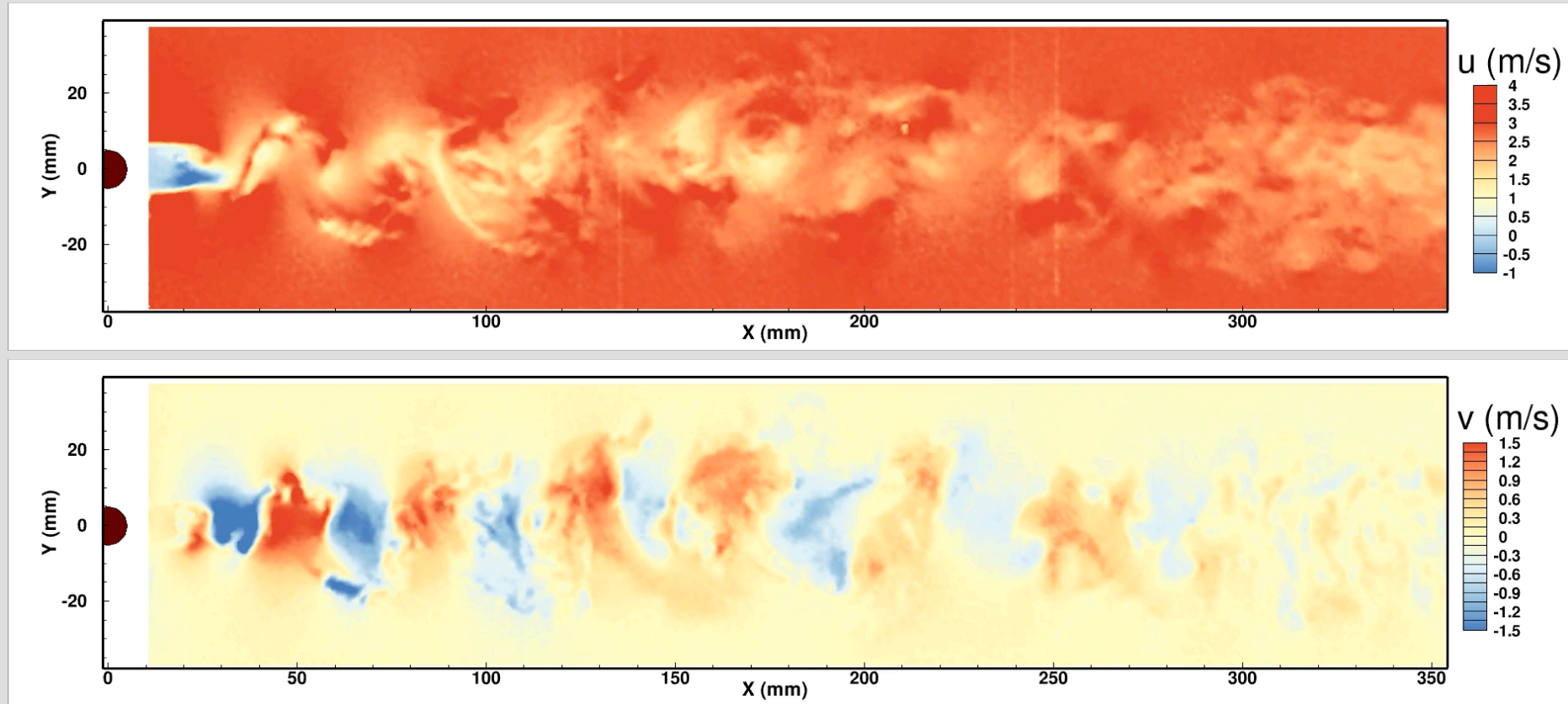
Exemple de champ de vitesse ($400 \times 300 \text{ mm}^2$) obtenu par PIV dans une flamme de chaudière industrielle 1 MW (Honoré, 2001).

Vélocimétrie par images de particules (PIV) - Applications

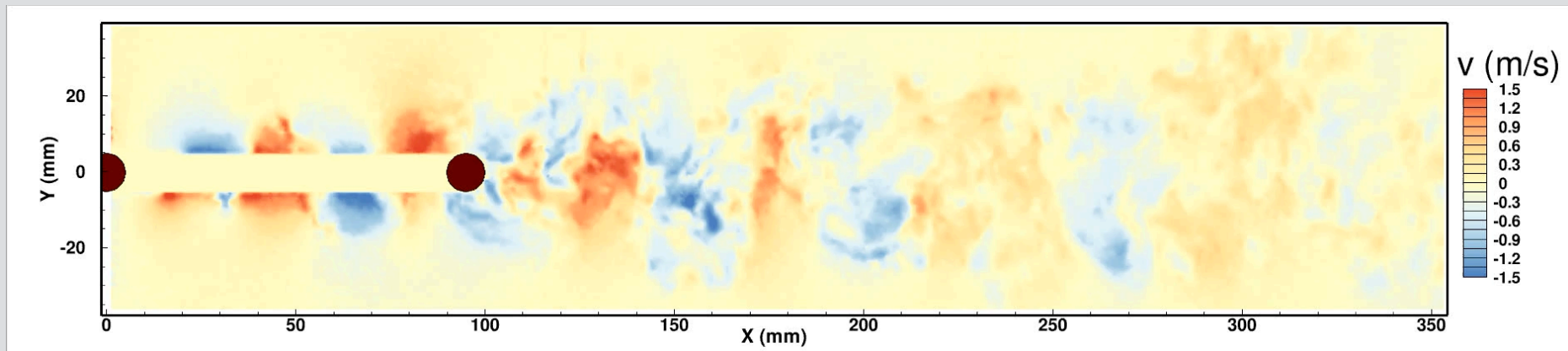
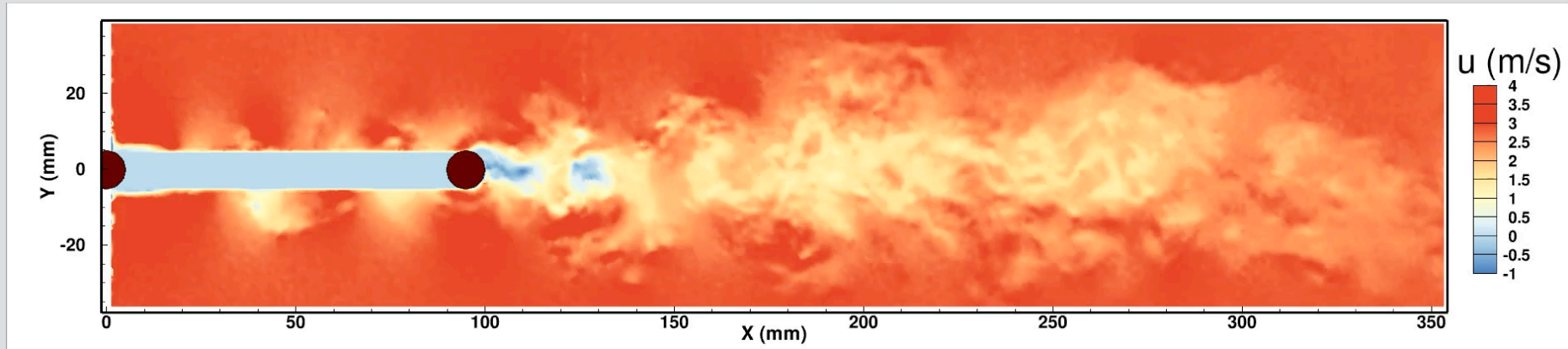


Exemple de champ de vitesse ($600 \times 600 \text{ mm}^2$) obtenu par PIV dans l'habitacle intérieur d'une automobile (Aronson et al., 2000).

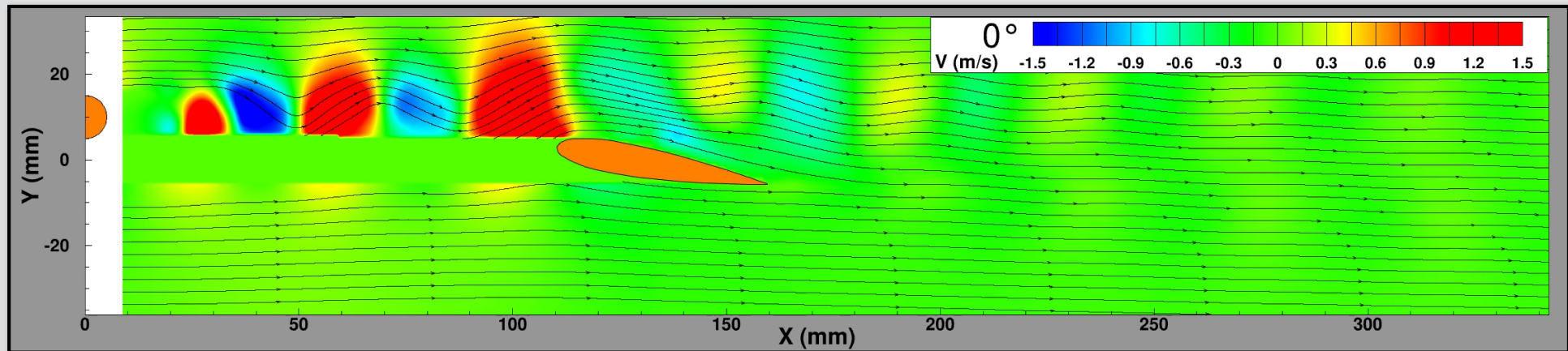
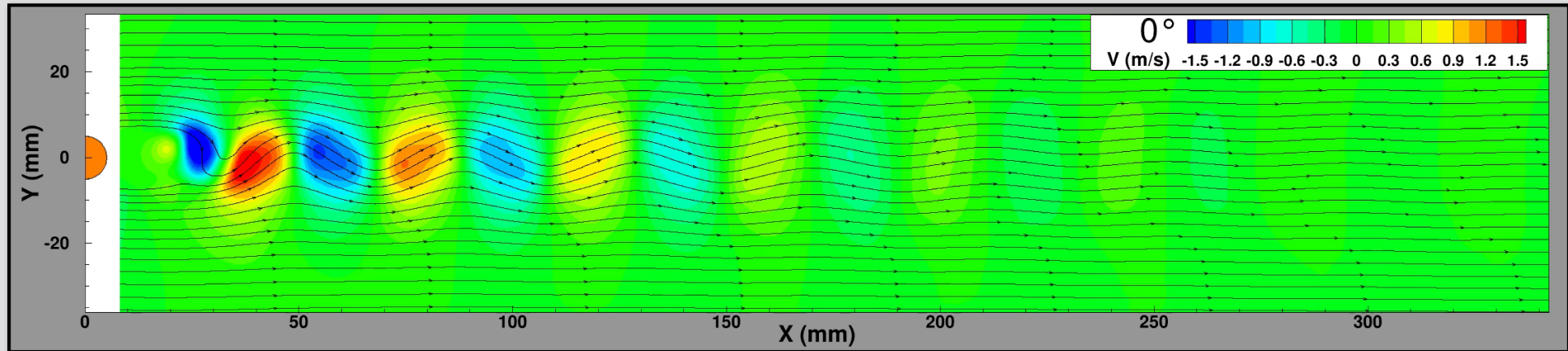
Single cylinder wake ($Re = 3000$) - Time Resolved PIV(5 to 20 kHz)



Double cylinder wake (Re = 3000) - Time Resolved PIV (5 to 20 kHz)



Wake interactions (Phase reconstruction)



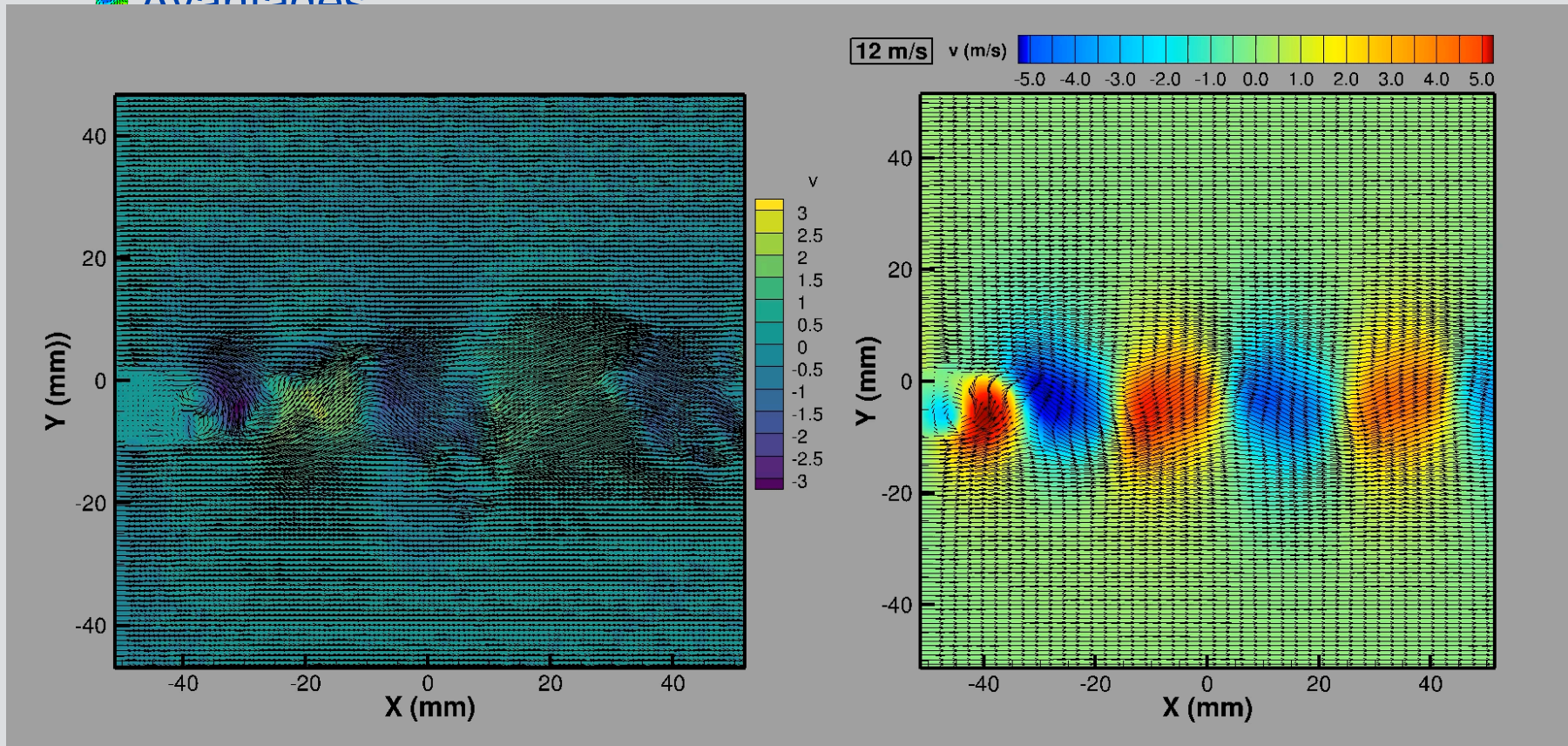
Ecoulement en aval d'un cylindre

● Remise en phase par post-traitement à partir d'enregistrements non-phasés

● enregistrements non-phasés

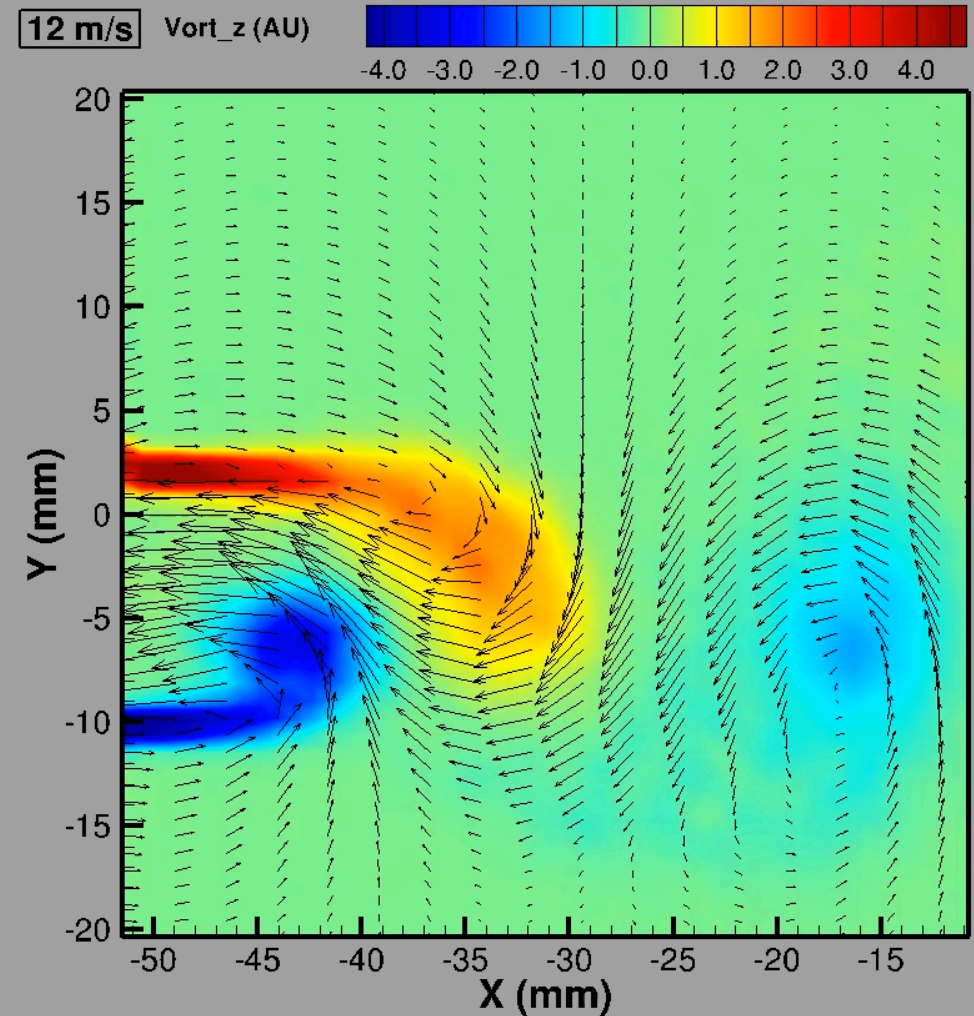
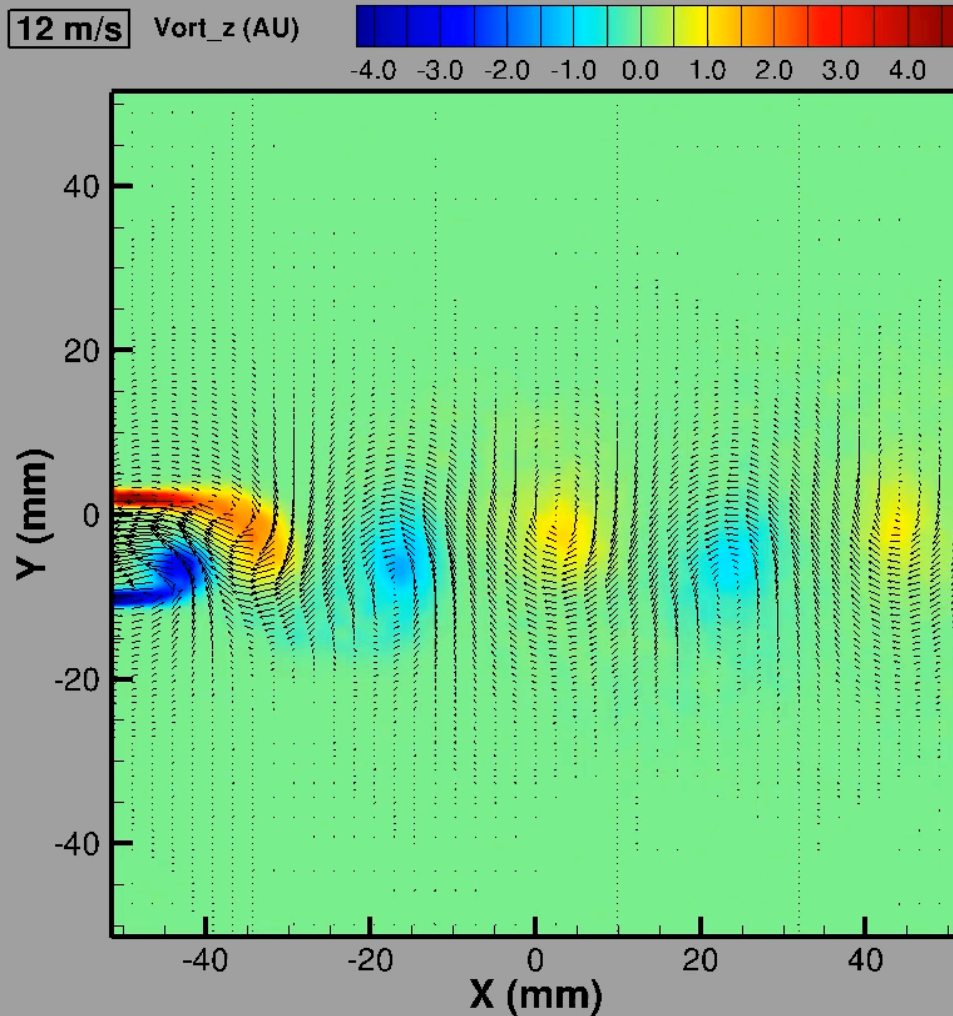
● Avantages

● Remise en phase



Mise en phase : Comparaison expérience 12 m/s

Vorticité moyenne

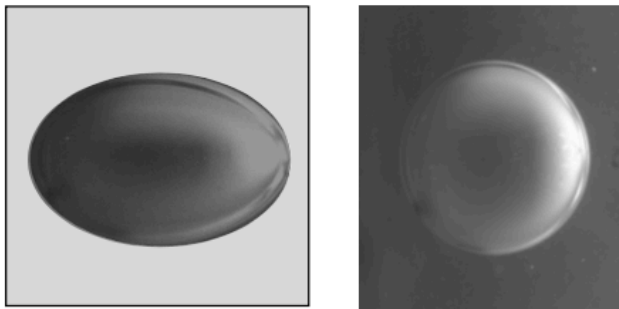
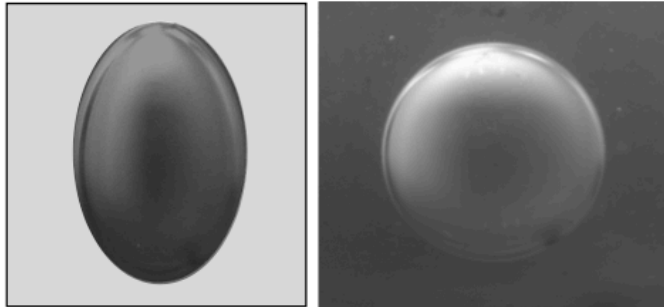


Ecoulements electrohydrodynamiques par PIV

Silicone in Castor oil

$$a_o = 2.2\text{mm}$$

$$E = 2\text{kV/cm}$$



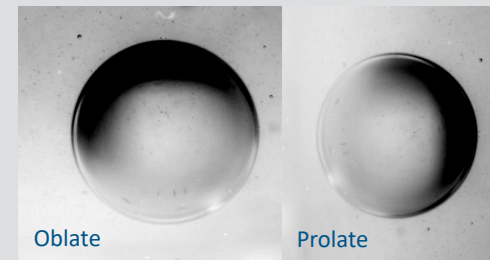
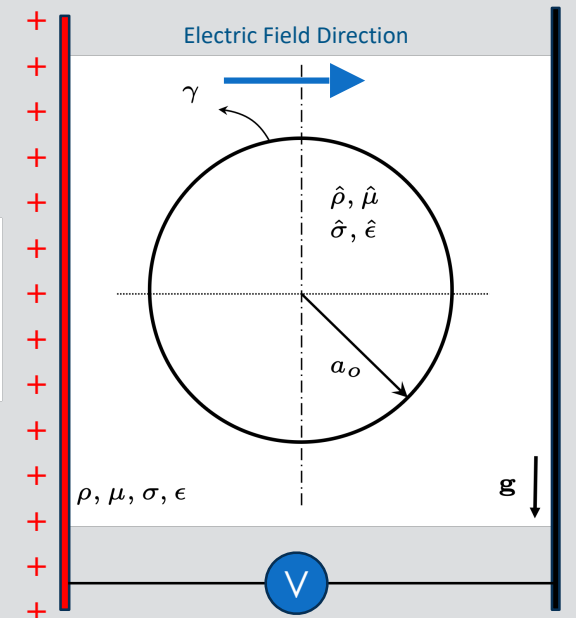
Castor in Silicone oil

$$a_o = 2.2\text{mm}$$

$$E = 1\text{kV/cm}$$

$\rho \rightarrow$ density
 $\mu \rightarrow$ viscosity
 $\sigma \rightarrow$ conductivity
 $\epsilon \rightarrow$ permittivity
 $\gamma \rightarrow$ interfacial tension

$$S = \frac{\hat{\epsilon}}{\epsilon}, R = \frac{\hat{\sigma}}{\sigma}, M = \frac{\hat{\mu}}{\mu}$$



$$\frac{R}{S} < 1$$

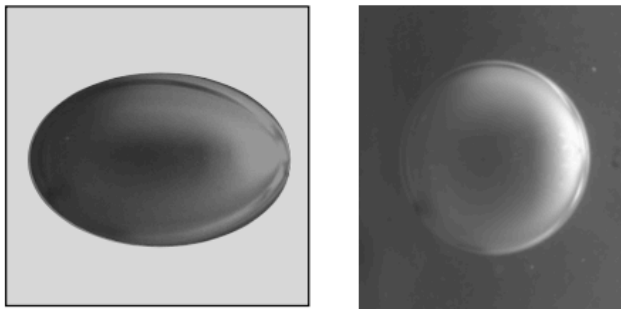
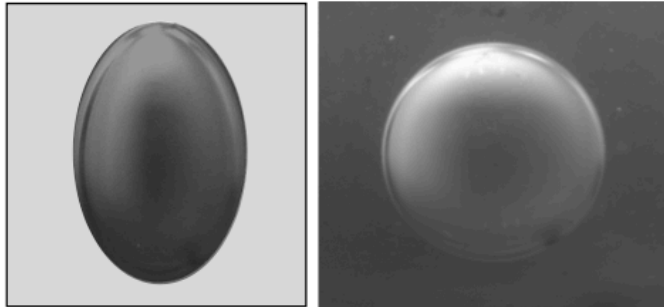
$$\frac{R}{S} > 1$$

Ecoulements electrohydrodynamiques par PIV

Silicone in Castor oil

$a_o = 2.2\text{mm}$

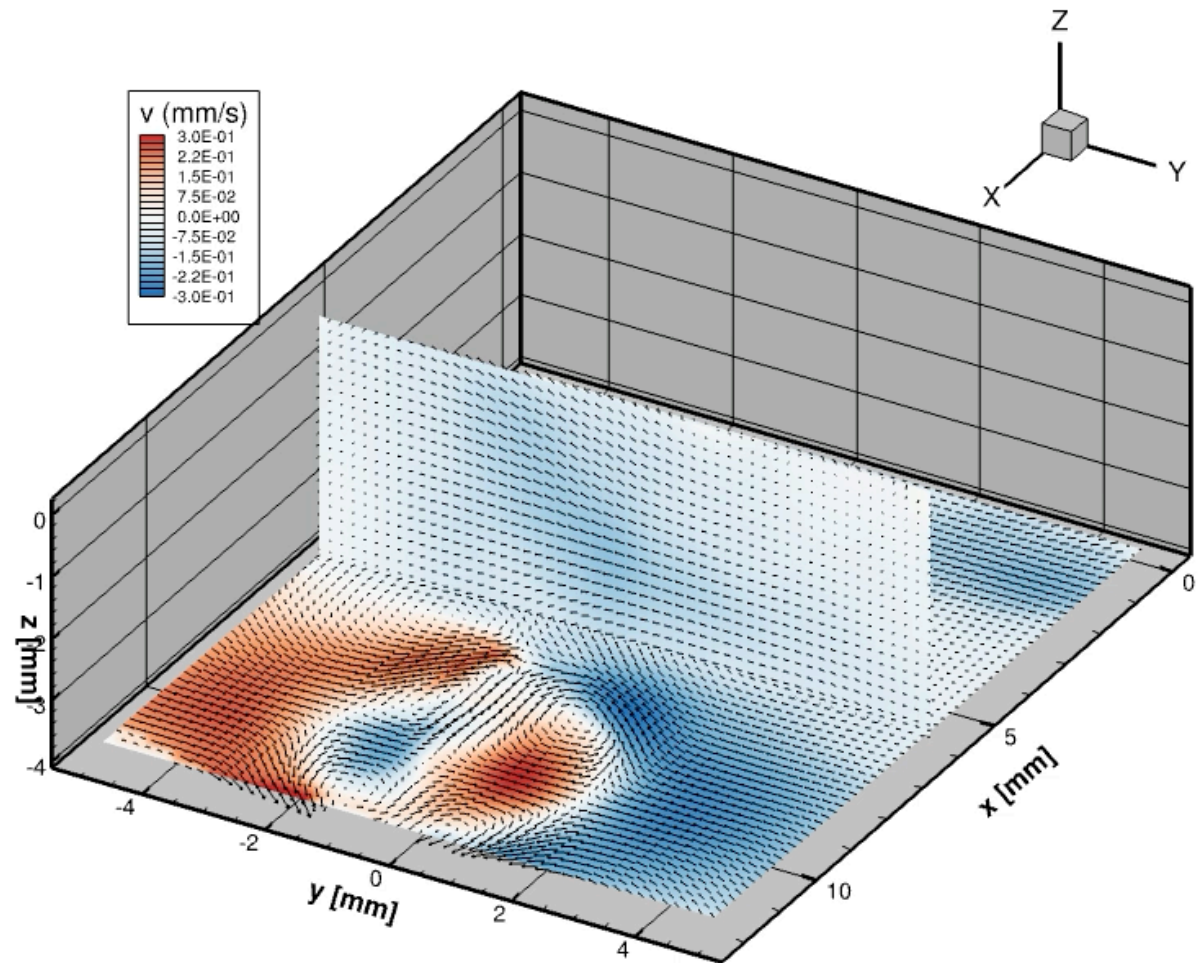
$E = 2\text{kV/cm}$



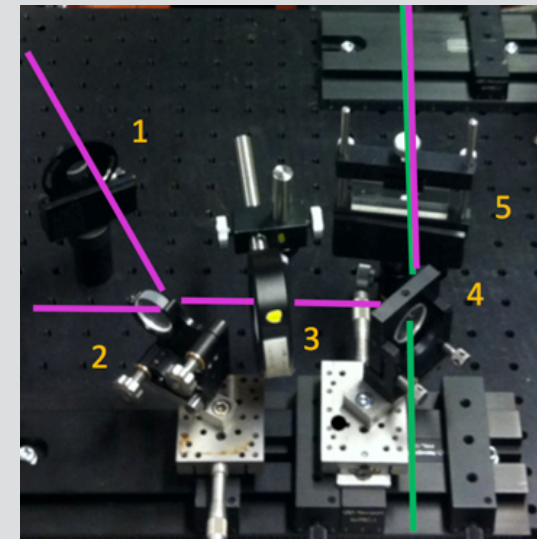
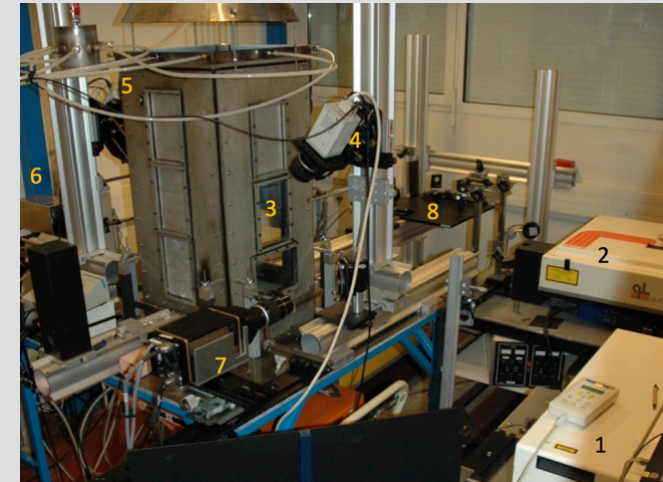
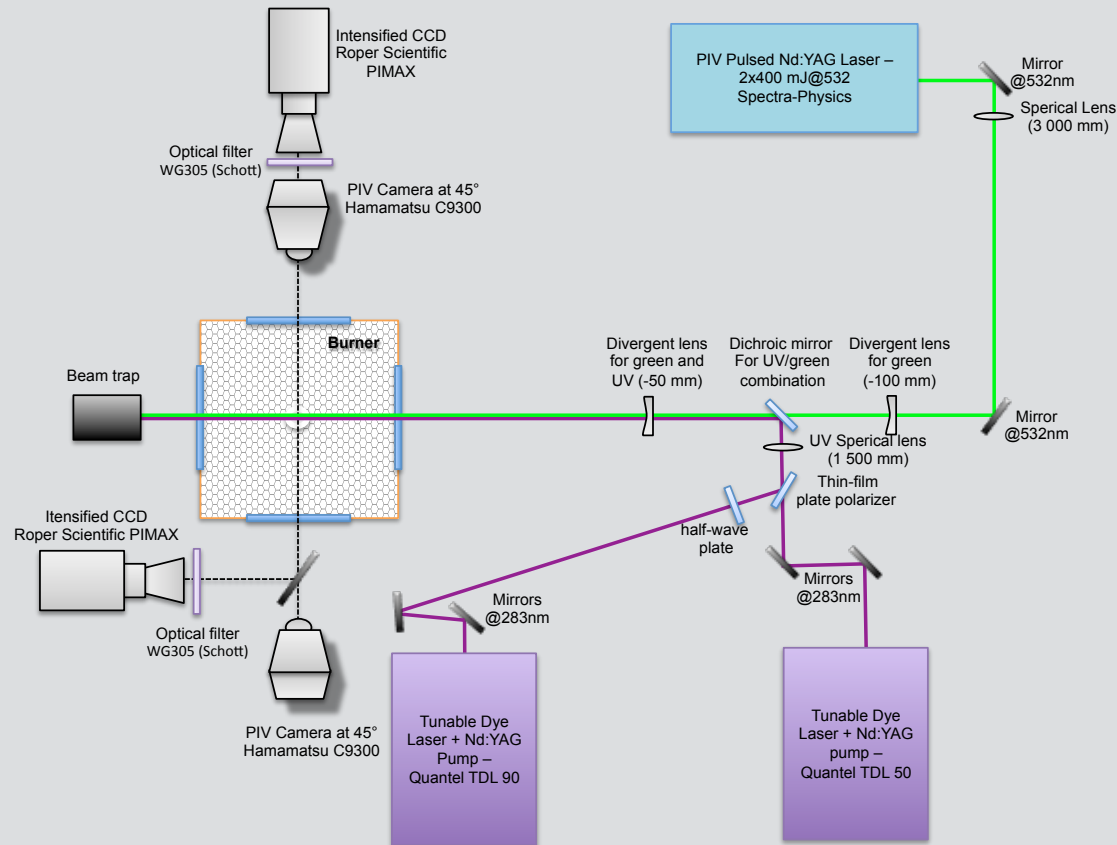
Castor in Silicone oil

$a_o = 2.2\text{mm}$

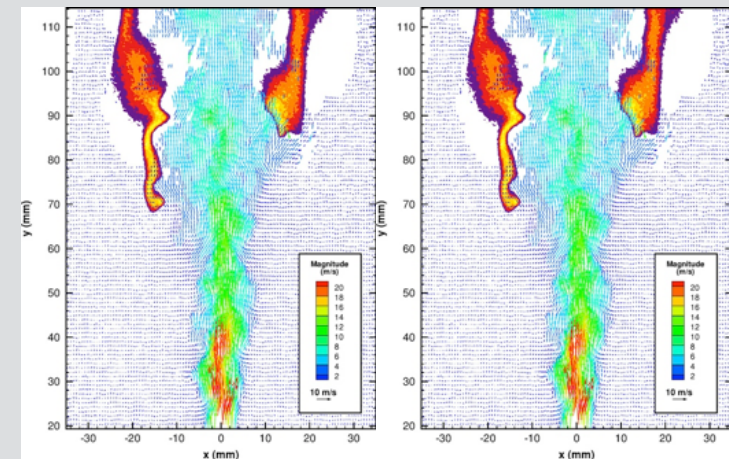
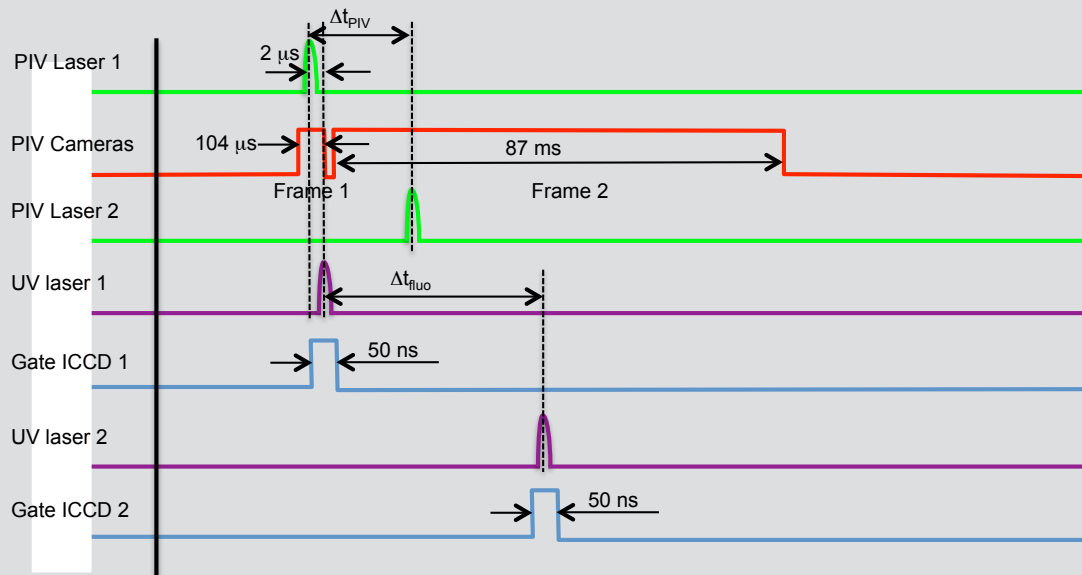
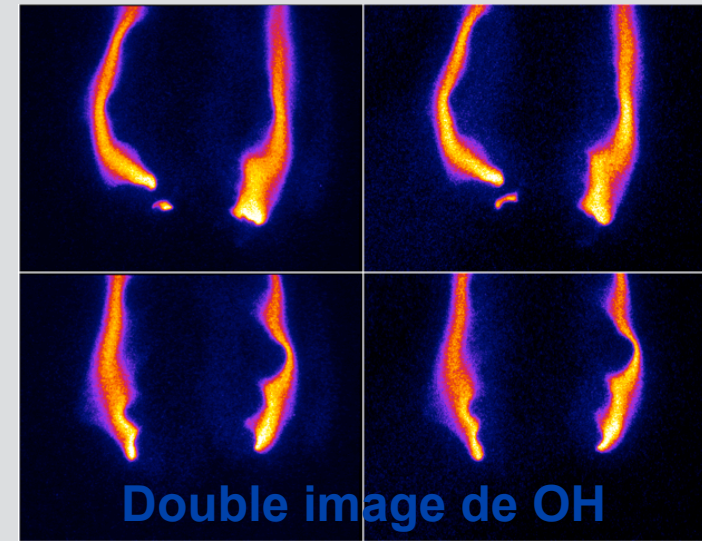
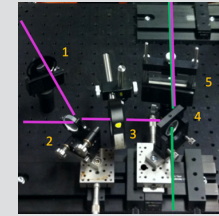
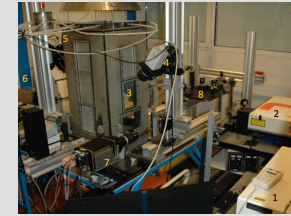
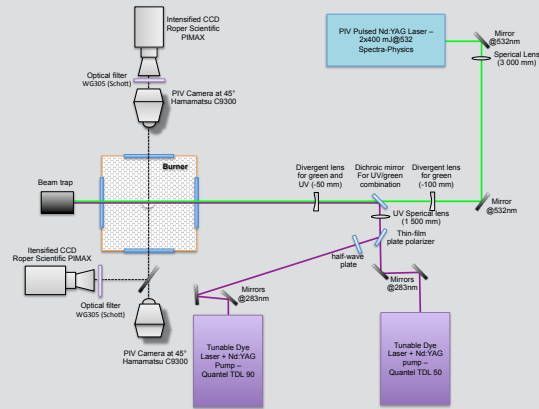
$E = 1\text{kV/cm}$



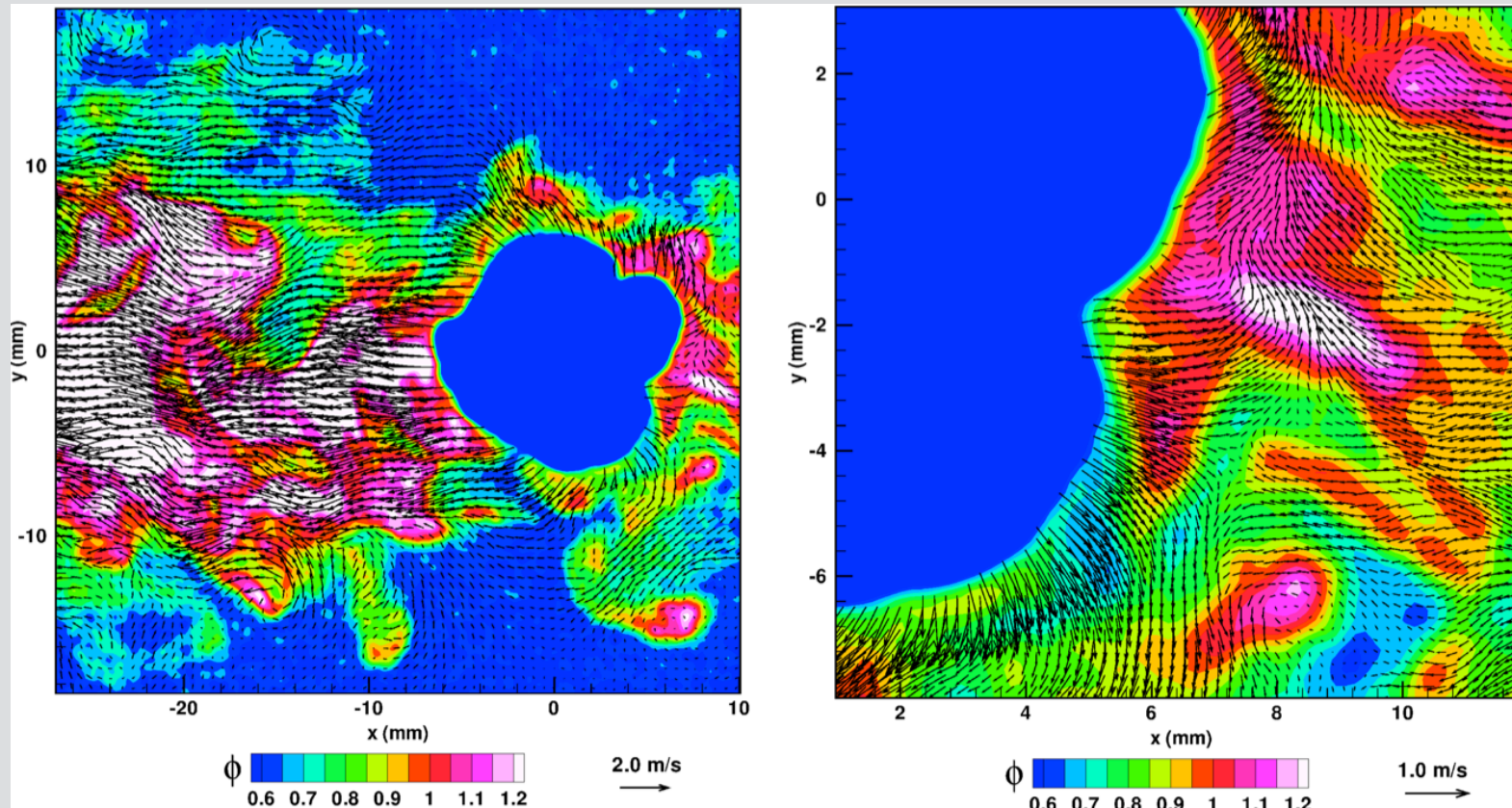
Couplage SPIV et double PLIF de OH (FP7 - AFDAR)



Couplage SPIV et double PLIF de OH (FP7 - AFDAR)



Vélocimétrie par images de particules (PIV) - Couplage



Vélocimétrie par images de particules (PIV) - Couplage

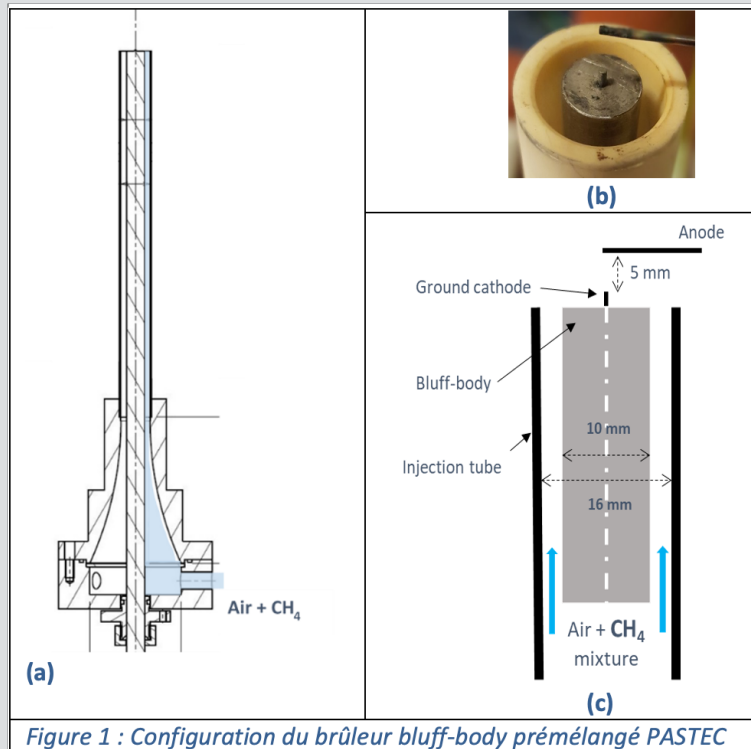


Figure 1 : Configuration du brûleur bluff-body prémélangé PASTEC

Stabilisation de flamme par décharge NRP

10ns, 7kV, 1,8mJ/pulse, 20kHz

3% de la puissance thermique flamme

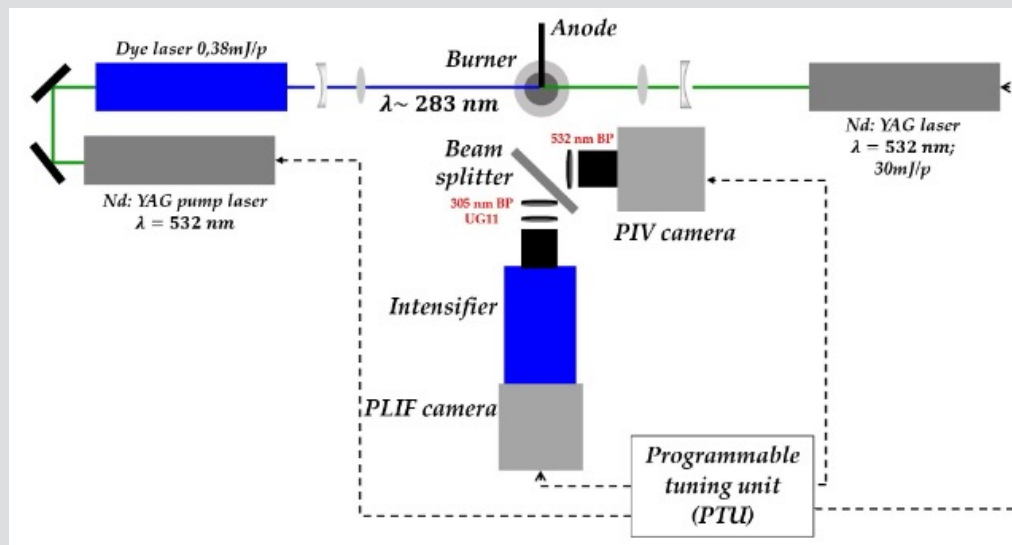
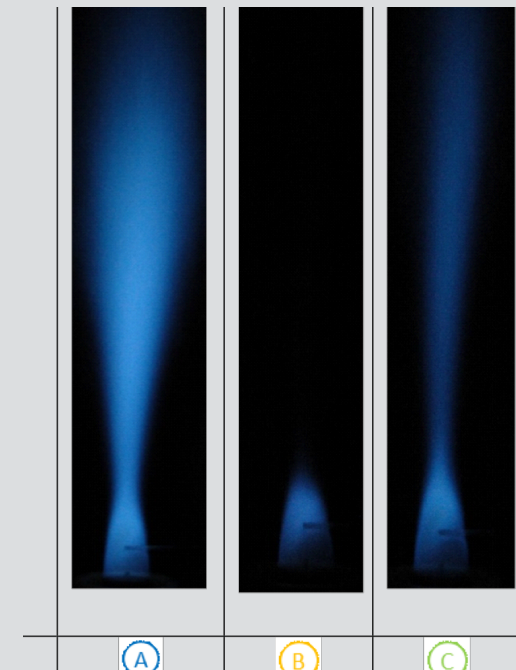
Etude de 3 conditions:

flamme stable proche stoechio A

flamme instable $fi=0,8$ B

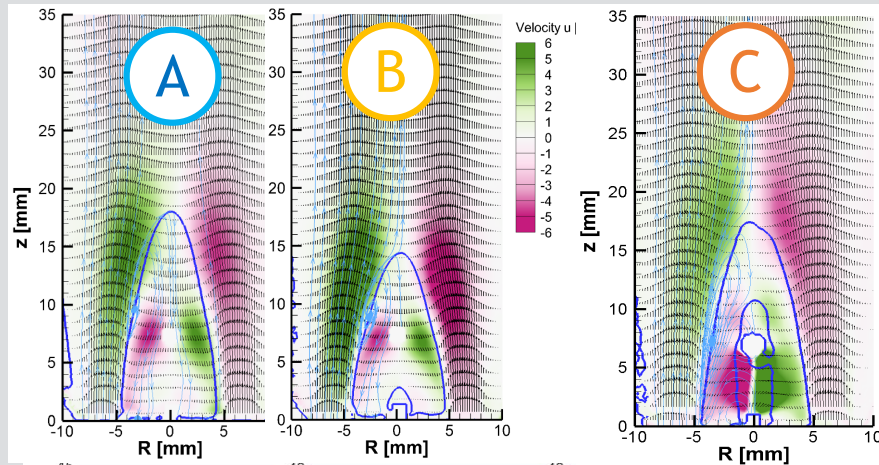
flamme instable $fi=0,8$ stabilisée par décharge C

Extension de la plage de stabilité par application de décharges

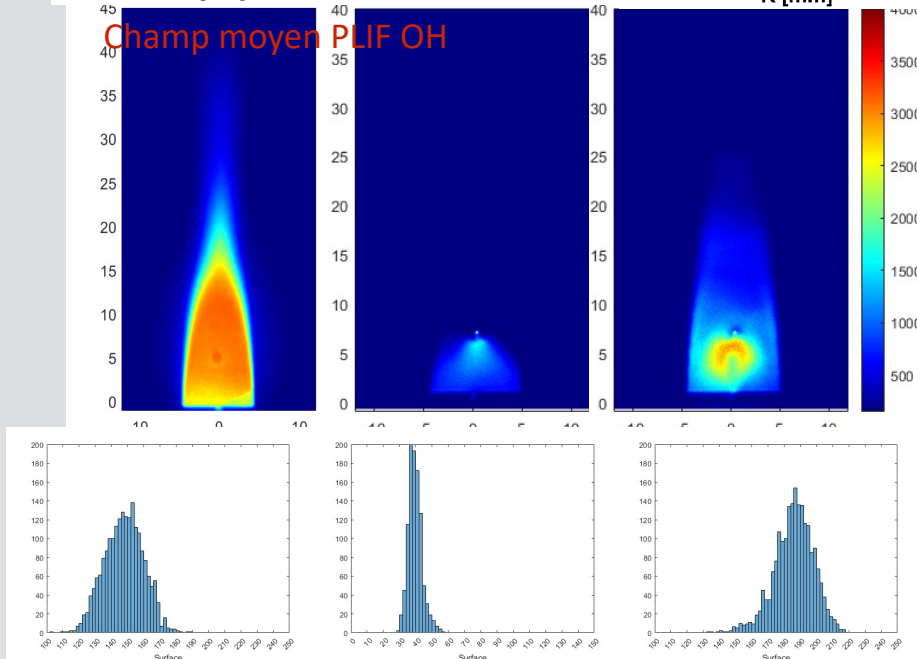


Vélocimétrie par images de particules (PIV) - Couplage

Champ moyen de vitesse , vitesse radiale

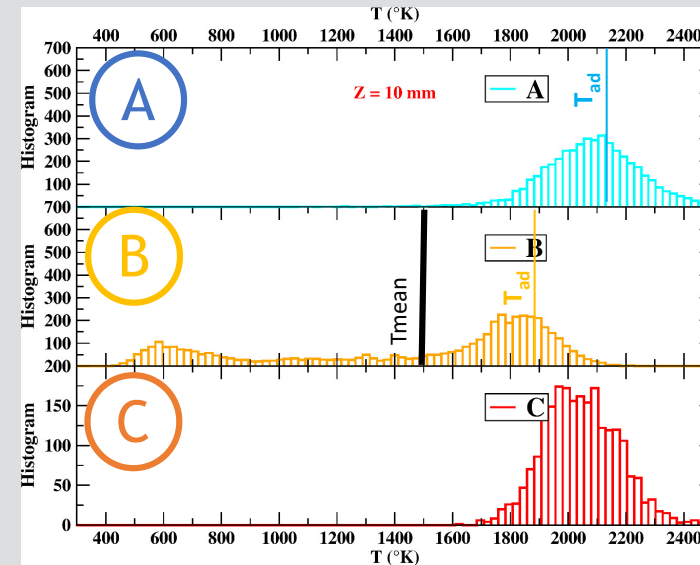
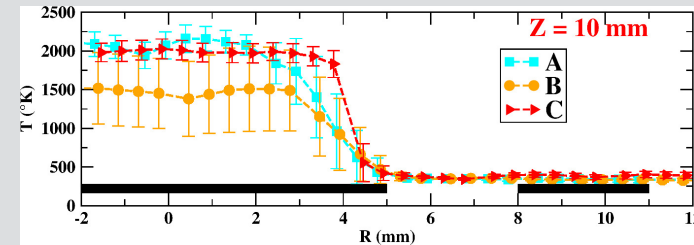


Champ moyen PLIF OH



Distribution de la surface de flamme

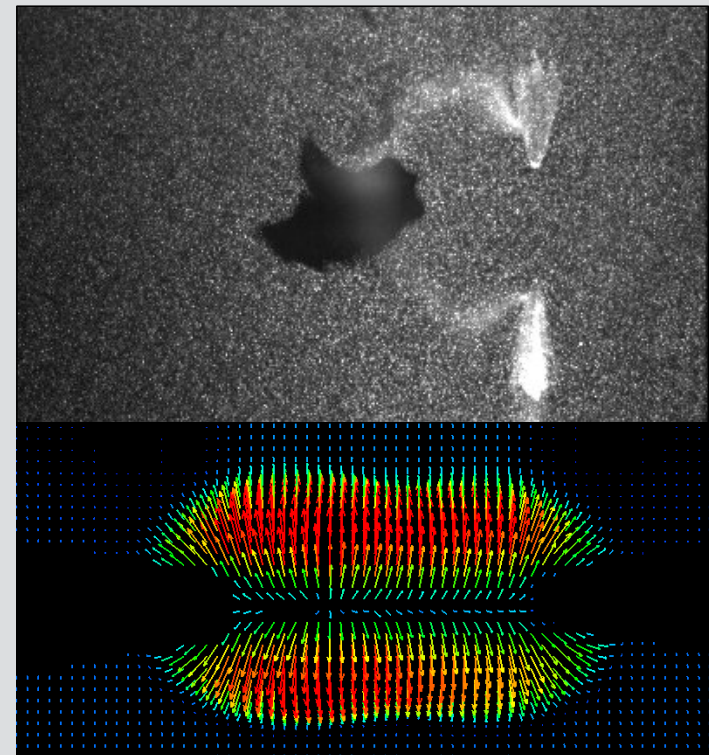
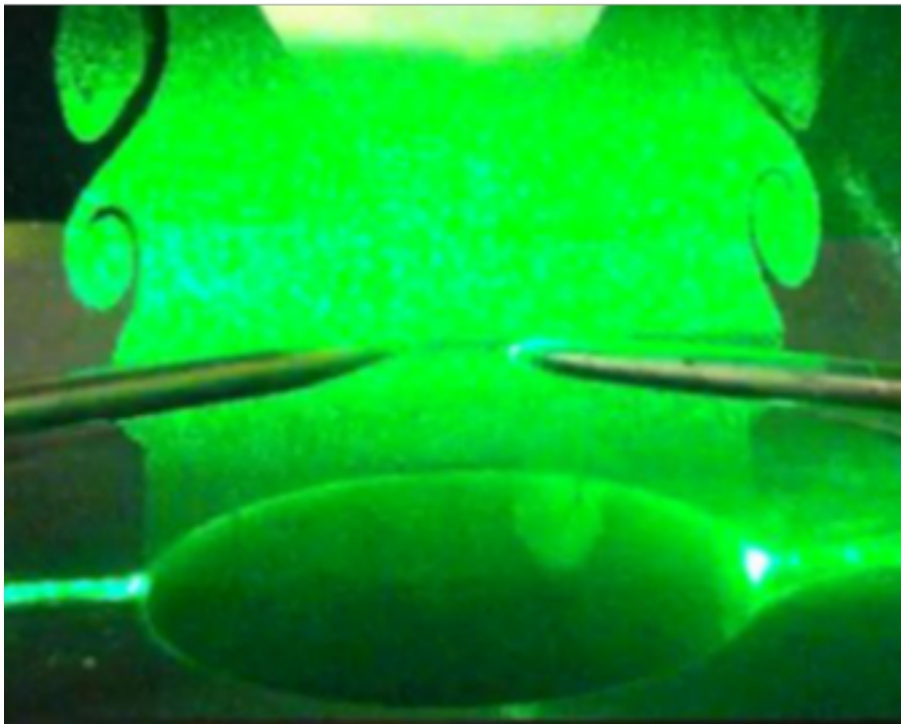
Profil de température moyenne : 1D SRS



Surface de la zone réactive retablie par l'application des NRP
La distribution de température monomodale centrée à 2100K est retrouvée pour la flamme C

Vélocimétrie par images de particules (PIV) - Application

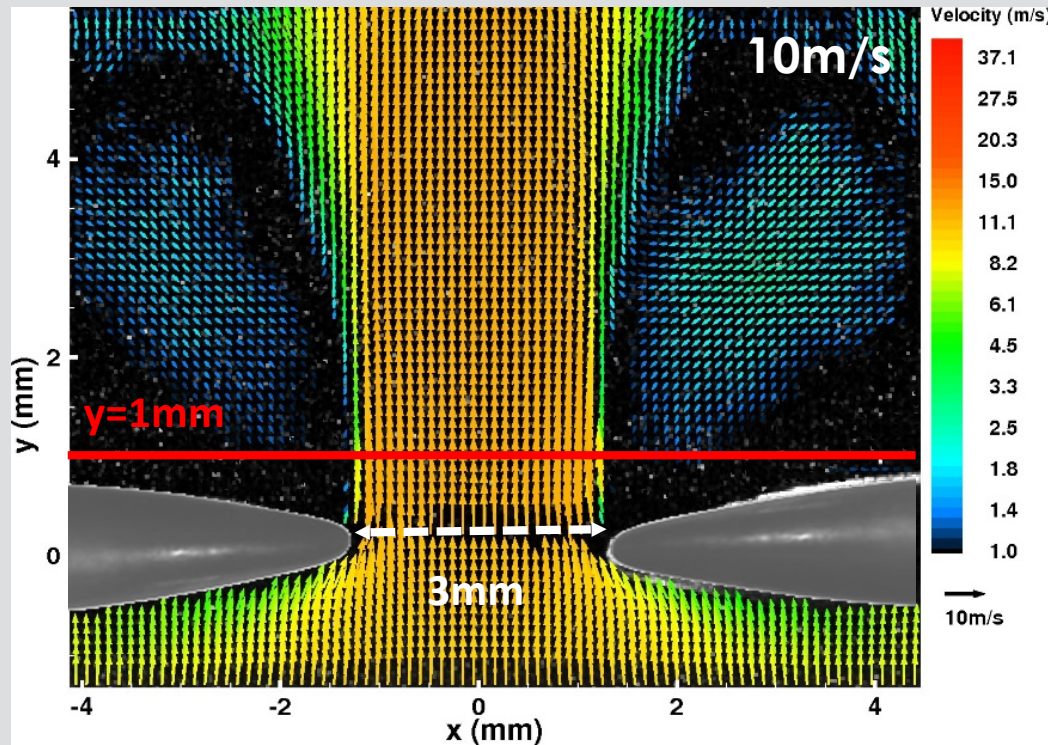
Interaction d'une décharge électrique avec un écoulement laminaire par diagnostics optiques



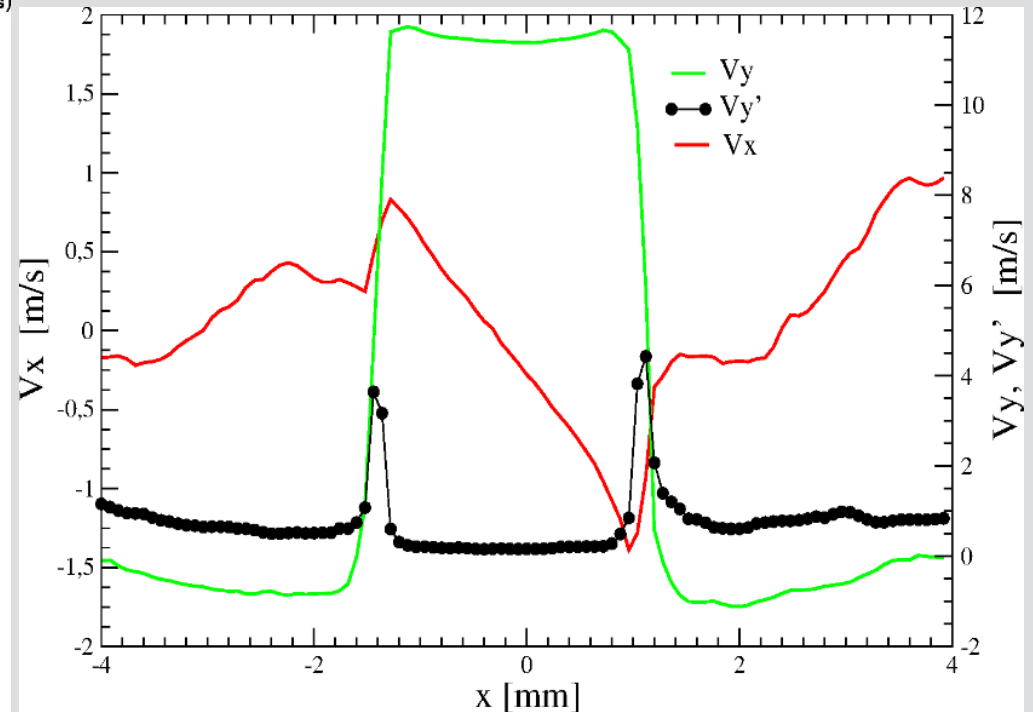
Vélocimétrie par images de particules (PIV) - Application

Caractérisation de la décharge en écoulement laminaire – conditions initiales

Champ de vitesse sans décharge (PIV) – vitesse de sortie soufflerie 10 m/s



Profil de vitesse @ $y=1\text{mm}$ 2m/s



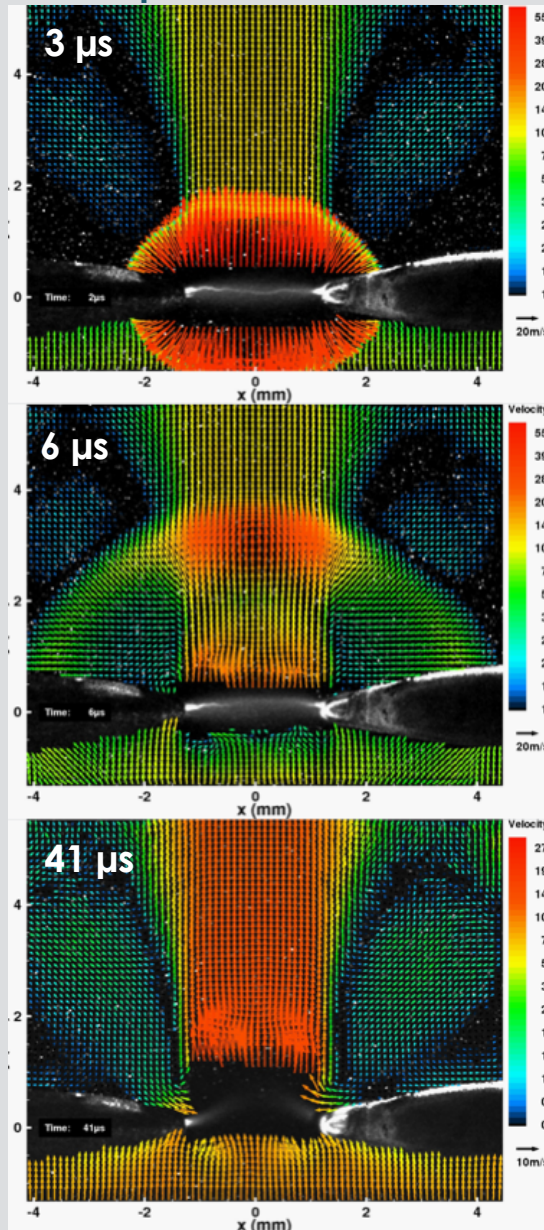
Fluctuations négligeables entre les électrodes
Sillage généré derrière les électrodes:
fluctuations plus importantes en aval

Ecoulement stable et uniforme à la sortie de la soufflerie

Vélocimétrie par images de particules (PIV) - Application

Caractérisation de la décharge en écoulement laminaire – conditions initiales

Champ de vitesse sans décharge (PIV) – vitesse de sortie soufflerie 10 m/s



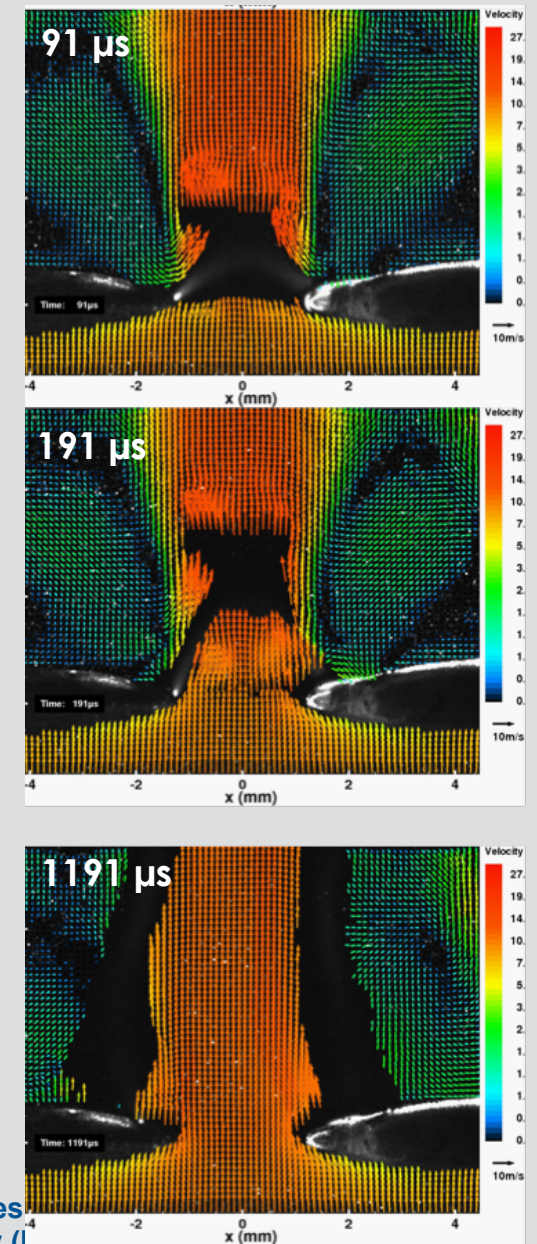
À 3 μs après le breakdown:
expansion rapide de l'onde de choc



à 41 μs:
Entrée de gaz le long des électrodes
en direction de la zone centrale



Temps longs:
Zone de gaz chaud transportée en
aval de l'écoulement et soumise aux
instabilités hydrodynamiques



Vélocimétrie par images de particules (PIV) - Application

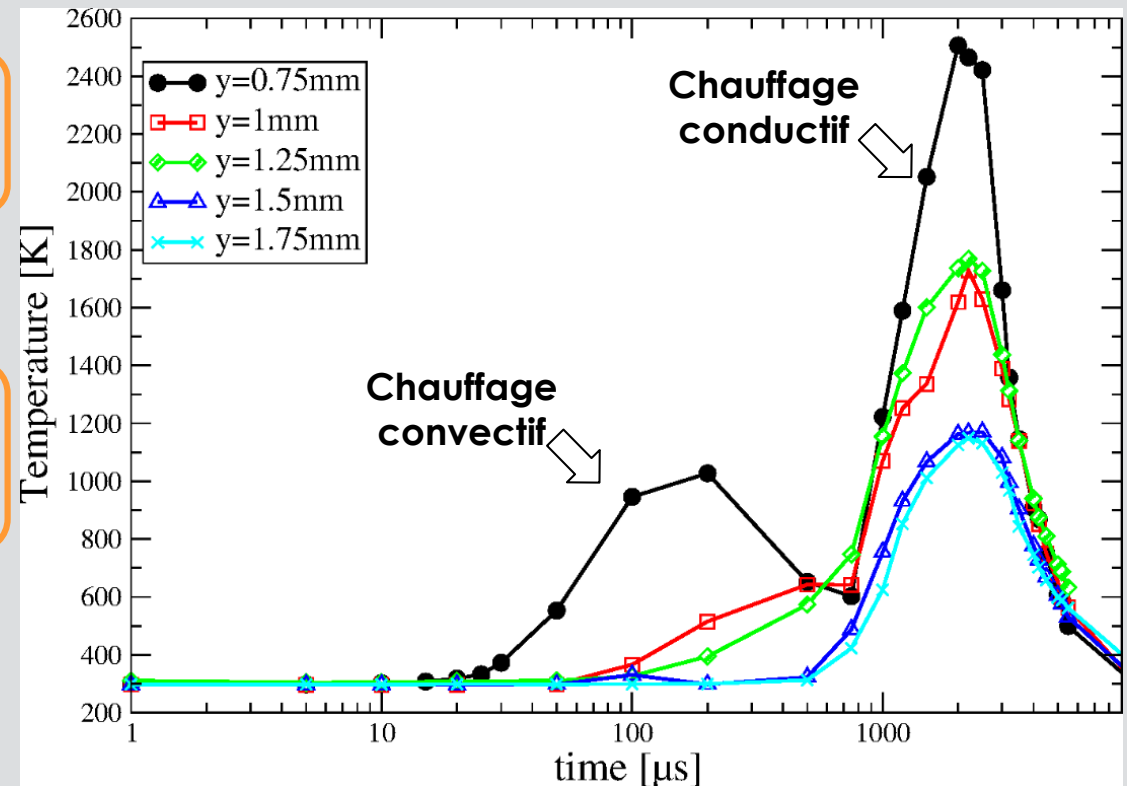
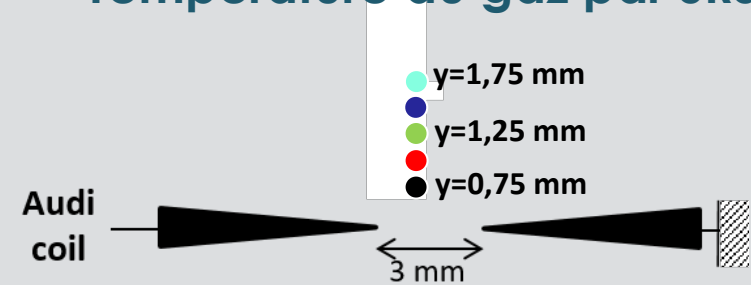
Température du gaz autour de la décharge

Chauffage convectif du gaz induit par l'expansion rapide du canal de gaz très chaud à la suite de l'onde de choc

Chauffage conductif du gaz par la phases de glow de la décharge

Expansion de la zone de gaz chaud à des positions en aval - refroidissement du gaz

Température du gaz par SRS



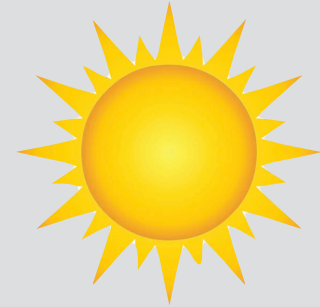
Acquisition

Source de lumière

Light sources for PIV or BOS techniques

● Natural light

- Spontaneous emission of radiation
- Polychromatic (different colors)
- Incoherent
- diverging rays (Intensity decrease)
- Continuous (or pulsed with short electric arc)



● LED (light-emitting diode)

- Monochromatic
- Continuous or pulsed (long duration)
- Incoherent
- Diverging rays difficult to focus



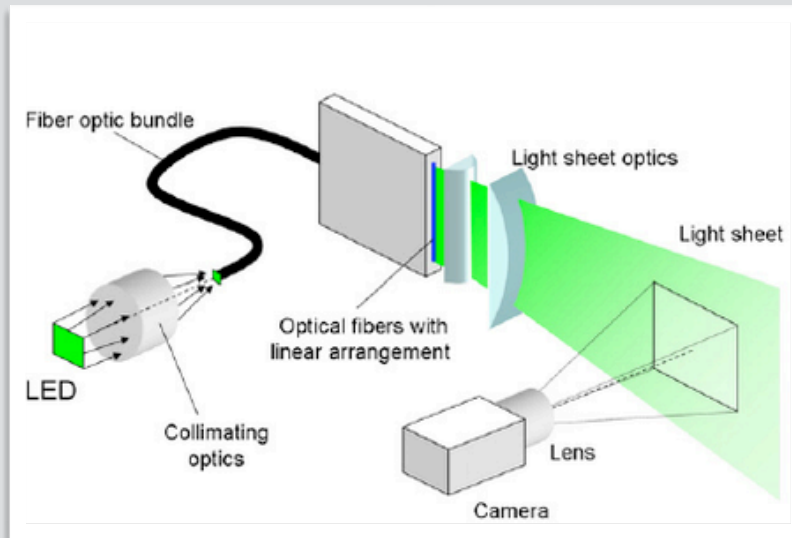
● Laser (Light Amplification by Stimulated Emission of Radiation)

- Stimulated Emission
- Monochromatic
- Coherent (interferences)

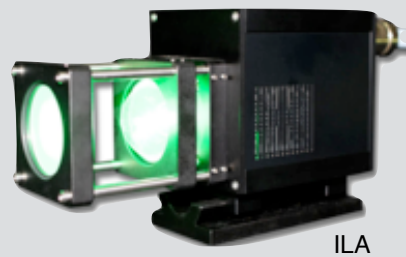
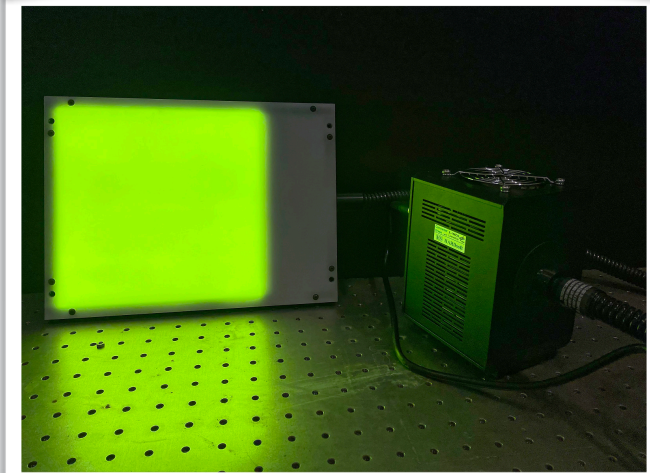
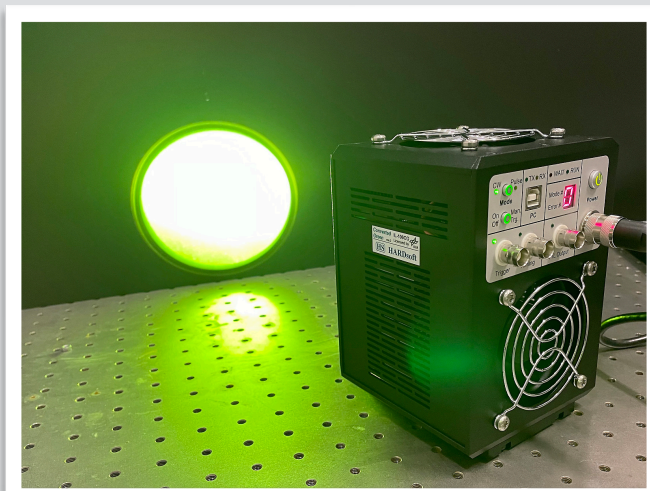


Light sources : LED

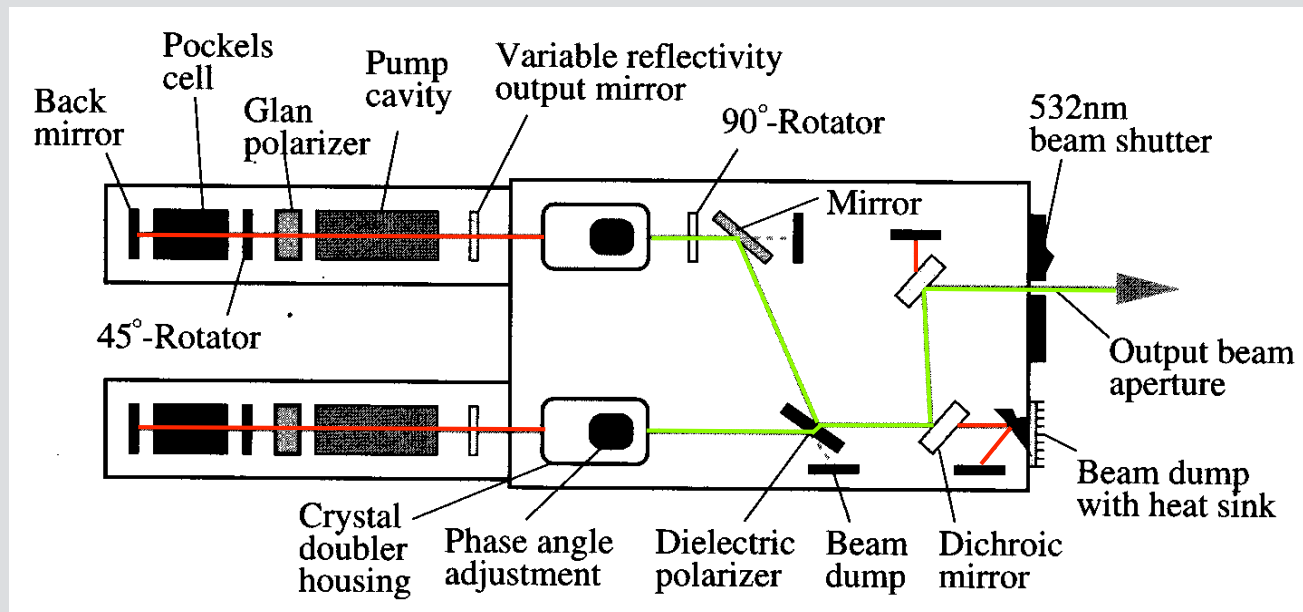
● Exemple of LED arrangement for PIV



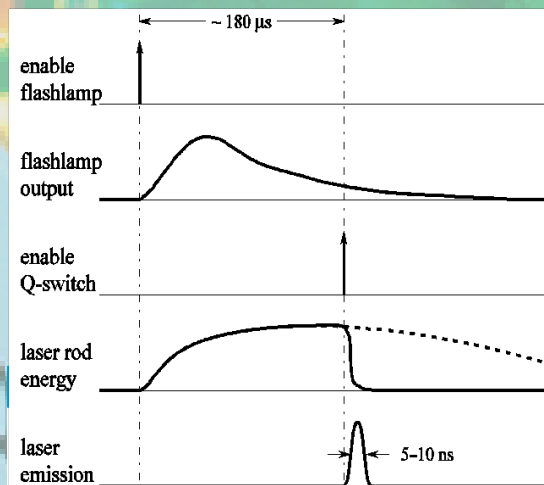
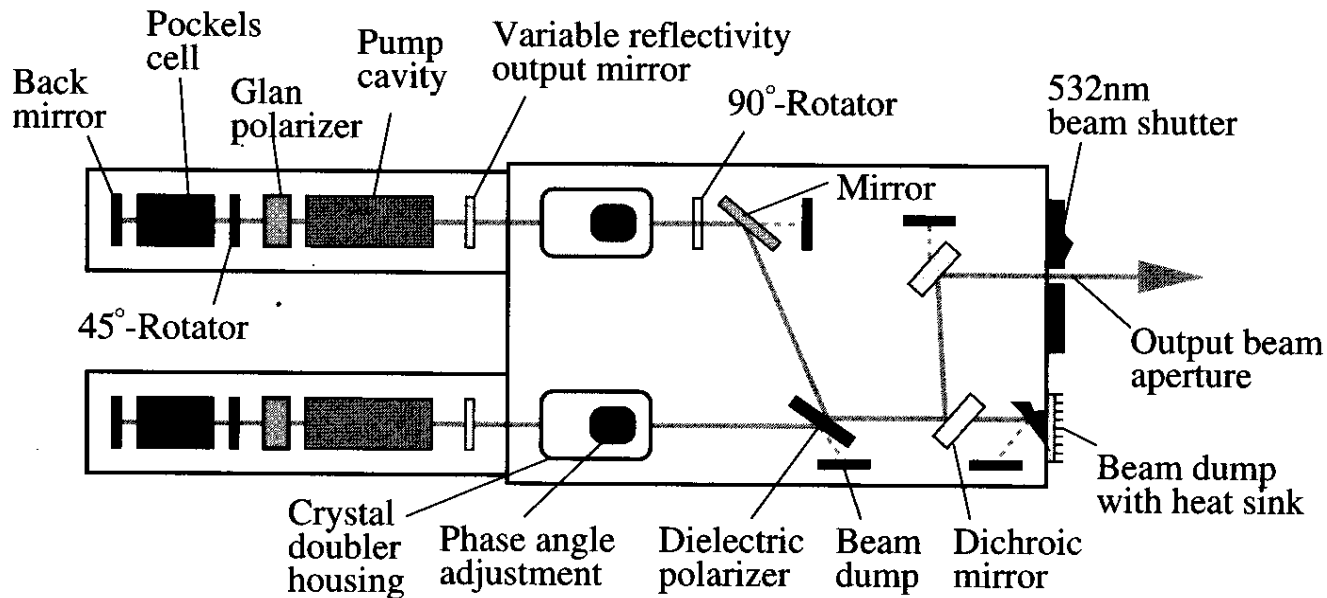
C. Willert et al. (2010)



LASER: Nd:YAG Laser for PIV - Dual cavities



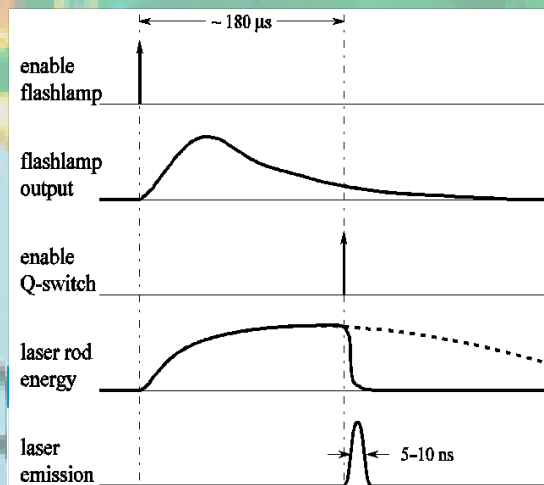
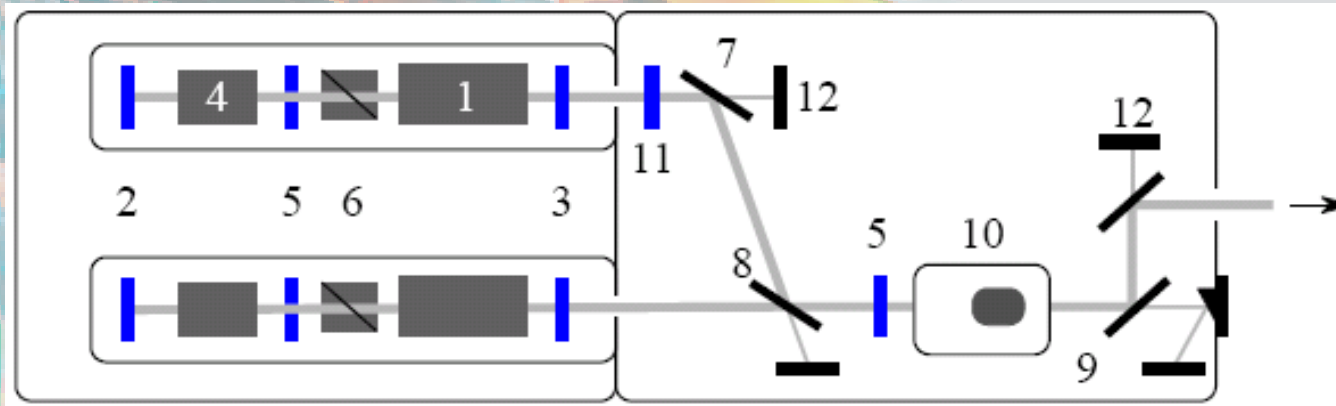
Vélocimétrie par images de particules (PIV) - Introduction



Laser

	Spectra Phys. PIV 400-10	Lee Lasers LDP-200MQG	New Wave Pegasus	Quantronix Darwin-Duo
Type	Nd:YAG	Nd:YAG	Nd:YLF	Nd:YLF
Wavelength [nm]	532	532	527	527
Repitition rate [kHz]	0.01	1 - 10	1 - 10	0.1 - 10
Power [mJ]	400 [@ 10Hz]	20 [@ 1 kHz]	10 [@ 1 kHz]	22.5 [@ 1 kHz]
Beam diameter [mm]	9	5	1.5	2
Beam divergence [mrad]	0.5	4	3	8
Pulse width [ns]	5 - 8	?	180	120

Vélocimétrie par images de particules (PIV) - Introduction

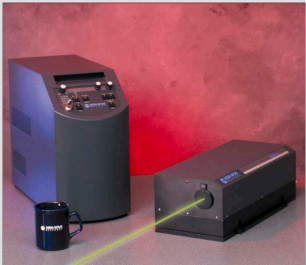


Laser

	Spectra Phys. PIV 400-10	Lee Lasers LDP-200MQG	New Wave Pegasus	Quantronix Darwin-Duo
Type	Nd:YAG	Nd:YAG	Nd:YLF	Nd:YLF
Wavelength [nm]	532	532	527	527
Repetition rate [kHz]	0.01	1 - 10	1 - 10	0.1 - 10
Power [mJ]	400 [@ 10Hz]	20 [@ 1 kHz]	10 [@ 1 kHz]	22.5 [@ 1 kHz]
Beam diameter [mm]	9	5	1.5	2
Beam divergence [mrad]	0.5	4	3	8
Pulse width [ns]	5 - 8	?	180	120

Laser: Main parameters

- Wavelength (532 nm, 527 nm...)
- Pulsed or continuous
- Repetitive rate (Hz)
- Pulse duration (ns: compared to flow)
- Pulse Energy (J)
- Polarisation (linear, circular)
- Energy stability (%)
- Beam diameter (near/far field)
- M²
- Divergence (mrad)
- Coherence length (m)
- Pointing stability (μrad)
-



PIV Series Pulsed Nd:YAG

Power Specifications												
Model ¹	PIV-200-*			PIV-300-				PIV-400-				
Rep Rate (Hz)	7.5	10	15	7.5	10	15	30	7.5	10	15	30	
Energy (mJ/p) ²												
532 nm	200	200	170	300	300	250	200	400	400	350	300	
355 nm ³	70	70	60	110	110	95	75	150	150	130	110	
266 nm ³	50	50	35	60	60	50	35	80	80	70	60	
CPO ⁴ 532 nm	135	135	100	200	200	175	150	250	250	225	200	

* All PIV systems come standard with WWF heat exchangers except the unseeded PIV-200 7.5 and 10 Hz which come standard with A/W heat exchangers.

Performance			
Wavelength	Pulse Width ⁵	Short Term Energy Stability ⁶	Long Term Power Drift ⁷
	5-10 ns	± 5 %	< 5 %
532 nm	Beam Divergence ⁸	Pointing Stability ⁹	Timing Jitter ¹⁰
	< 0.5 mrad	< ± 100 μrad	< 0.5 ns

Mode	Standard Fit		Pulse
Spatial Mode Profile ¹¹	Standard Fit	ESM Fit ¹²	Line Width ¹³
Near Field (1m)	> 80%	> 80%	Standard < 1.4 cm ¹
Far Field (∞)	> 95%	> 95%	Injection Seeded < 0.005 cm ¹
Modulation ¹⁴	< 50%	< 25%	Coherence Length > 2 m
Beam Diameter ¹⁵	PIV-200, -300: 8 mm	PIV-400: 9 mm	Tunability ¹⁶ > 30 GHz

Note: Additional nonstandard options are available such as dual harmonic generators and double pulse options. Contact factory for specialized systems.

1. All specifications subject to change without notice. Unless otherwise stated, specifications are given for Q-switched operation at 532 nm.

2. Harmonic energies are specified after separation using dichroic mirrors and using type II second harmonic generation (SHG) crystal.

3. Resonance additional IHS-XXX and external BD-s.

4. CPO - cross-seeded polarized option. Consequent output pulses are polarized orthogonal to one another. For other CPO Harmonics contact factory.

5. PIV-200 pulse widths are 8-10 ns. PIV-300, -400 pulse widths are 5-8 ns.

6. Pulse to pulse stability for >90% of pulses, measured over a 1 hour period.

7. Over an 8 hour period with temperature variations of <±3°C.

8. Full angle measured at FWHM points.

9. Long term average pointing drift on combined beams after warmup, over 8 hours ±3°.

10. rms jitter from Q-switch sync pulses, jitter is <1 ns rms when using the Model 6300 injection seeder, at 10 Hz, <1.5 ns at 15 and 30 Hz.

11. Near field spatial profiles measured 1 m from laser using a commercially available beam diagnostic system, 60% refers to the correlation between the actual beam profile and the best least squares fit Gaussian profile. Far field profiles are measured at the focal plane of a 2 m focal length lens.

12. Enhanced spatial mode options can be tailored to meet your application needs. To obtain >80% Gaussian fit, energy can be reduced by 30%.

13. Insertion losses for systems using the Model 6300 injection seeder are <10% at 532 nm, 355 nm, and 266 nm wavelengths.

14. Refer to the maximum deviation from the best-fit Gaussian profile measured in the near field (1 m) between the FWHM points.

15. Actual beam diameter will vary ±1 mm depending on laser configuration.

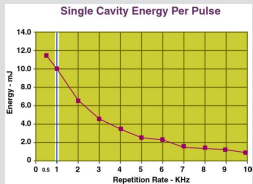
16. Temperature tuning of seeder controllable via BNC voltage.

Spectra-Physics
Spectra-Physics Lasers

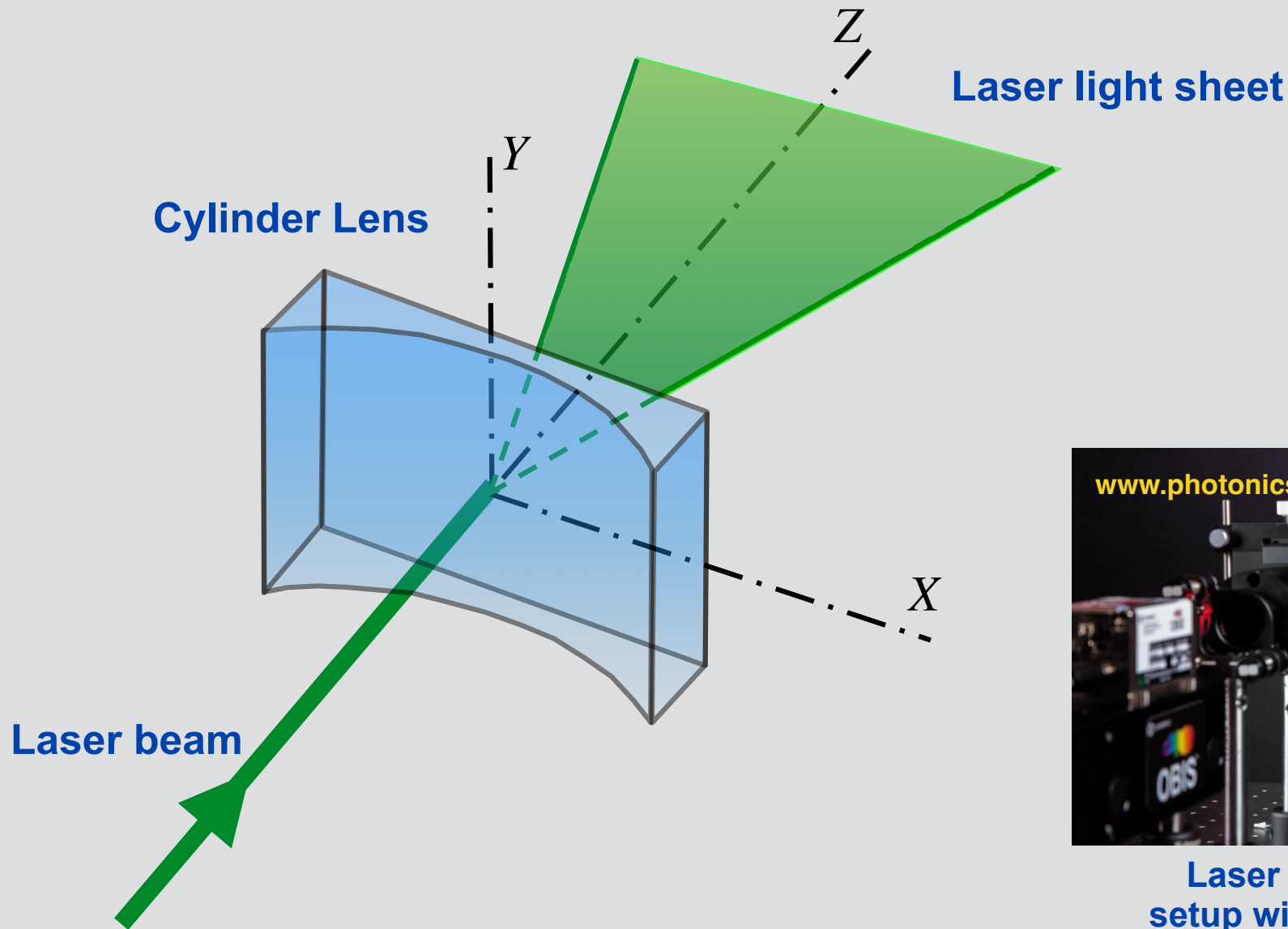
Performance Specifications

Wavelength	527 nm
Repetition Rate	
Dual Cavity System	2—20,000 Hz
Per Cavity	1—10,000 Hz
Energy	
Dual Cavity System	≥ 10mJ @ 2,000 Hz (2 x 1,000 Hz per cavity)
Per Cavity	≥ 10mJ @ 1,000 Hz
Power ¹ @ 1,000 Hz x 2	
Dual Cavity System	≥ 20 watts
Per Cavity	≥ 10 watts
Energy Stability ² (rms %) @ 2kHz, 20W	< 1%
Pulse Width ³ at 1kHz	< 180 ns
Beam diameter	1.5 mm
Divergence ⁴	≤ 3 mrad
Polarization	Vertical
Spatial mode	Multimode, M ² <8
Warm-up time—95% full power	≤ 10 min.

1. After 10 minute warm-up
2. RMS after 10 minute warm-up
3. Full width, half-maximum
4. Full angle for 86% of the energy, at 1/e²

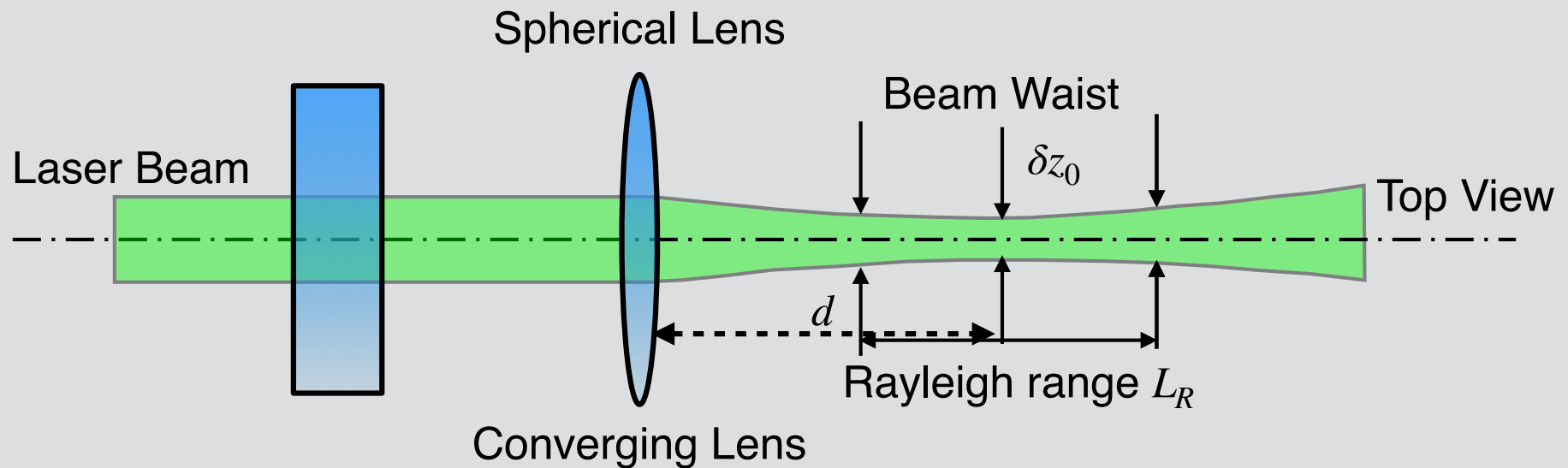
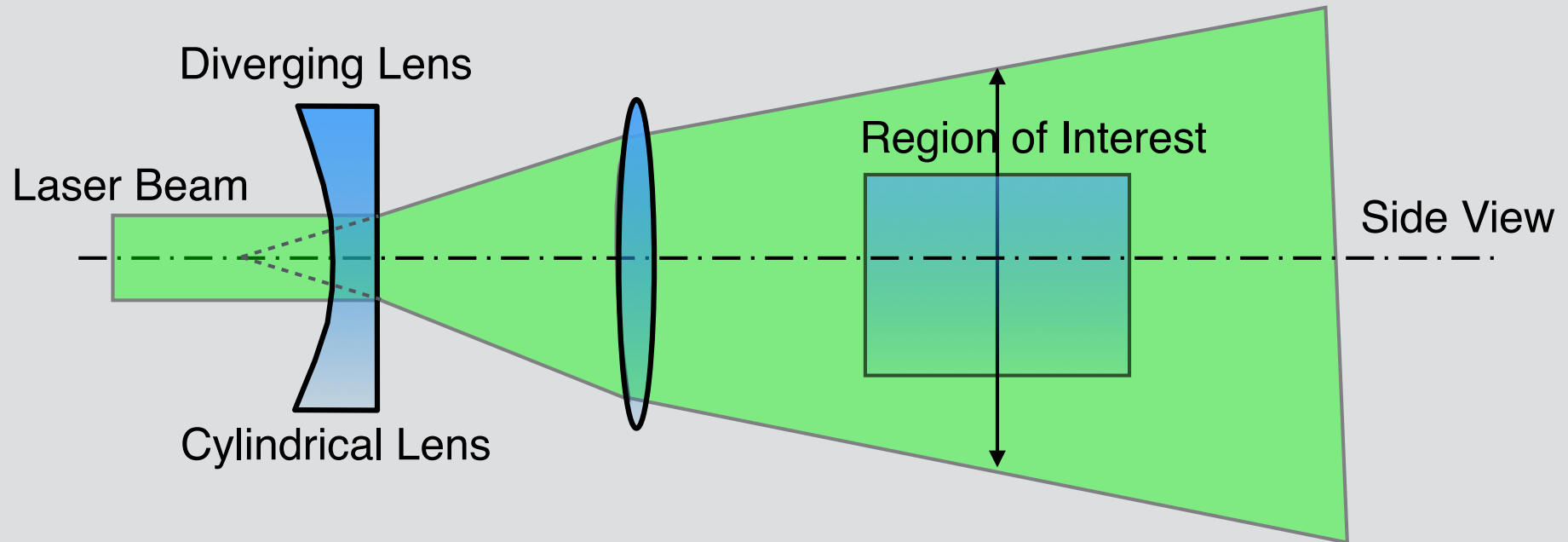


Laser: Beam shaping: Sketch of a cylindrical lens



Laser line generation
setup with a cylinder lens

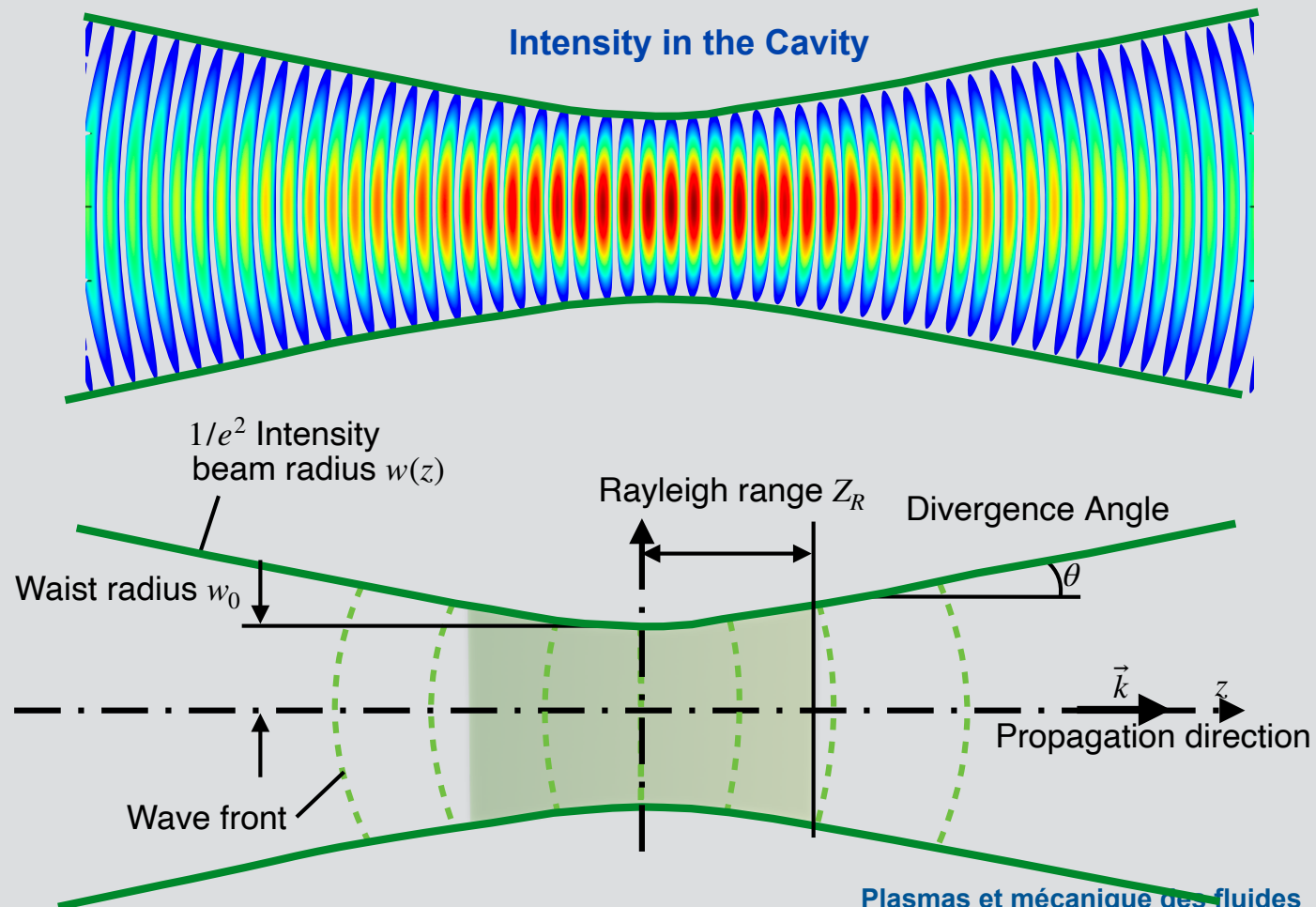
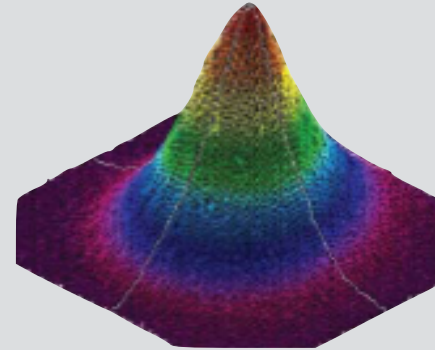
Laser: LS with a set of cylindrical and spherical Lenses



Other possibility: a set of two cylindrical lenses

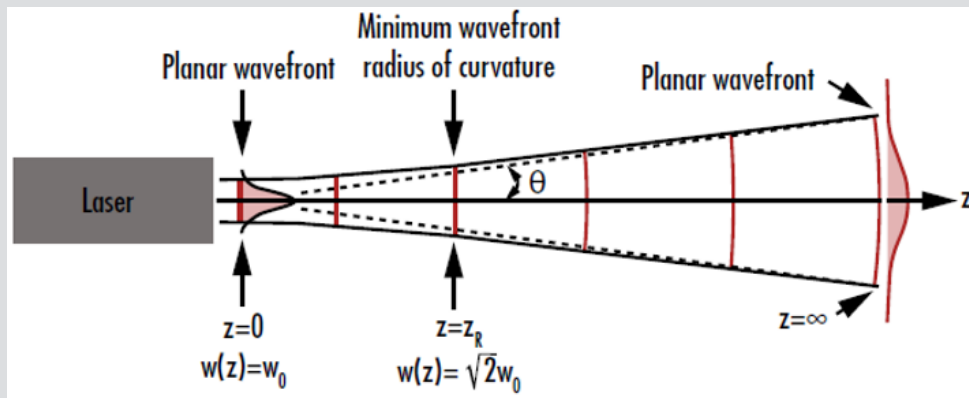
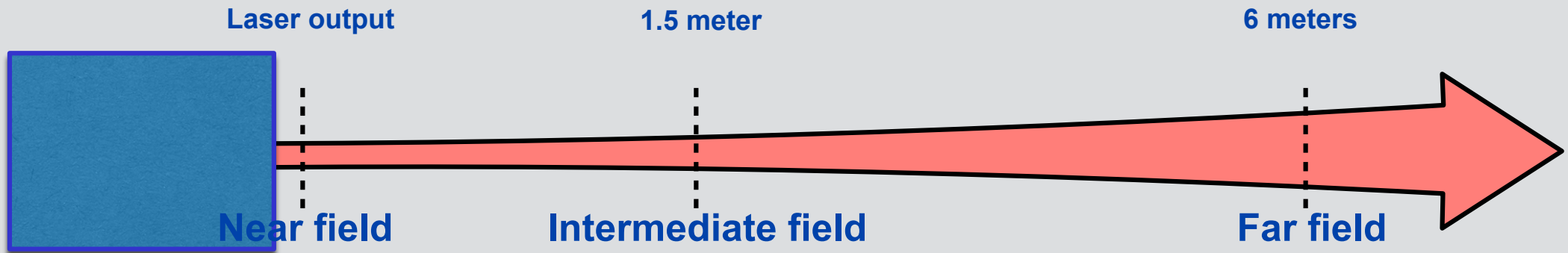
LASER: Beam profiles : Gaussian Beam

Measured beam profile at the output of a YAG laser



LASER: Divergence

Burn pattern on thermal paper at increasing distance

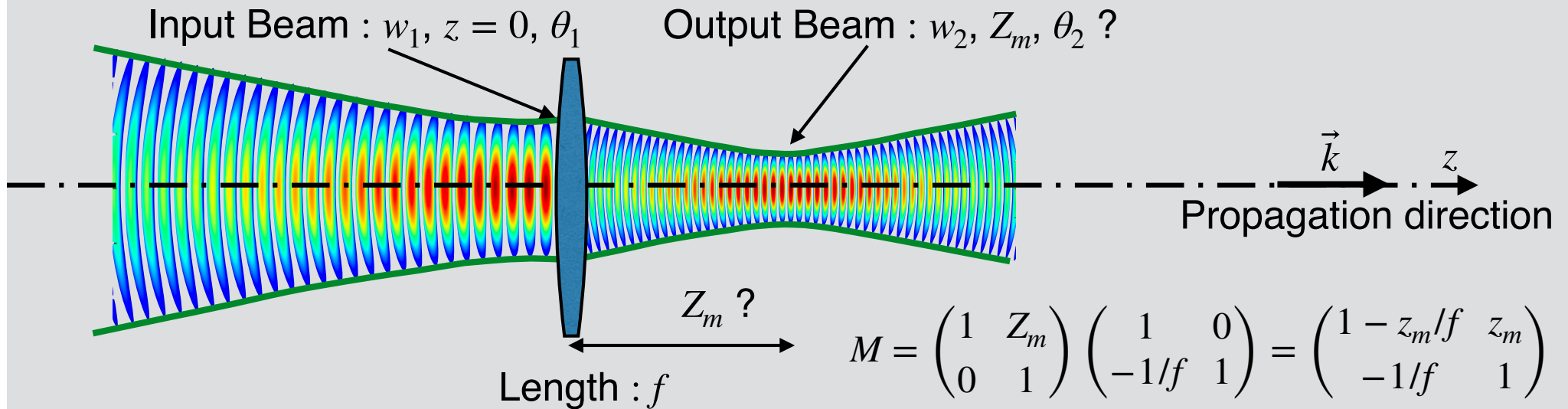


$$\text{Divergence: } \theta = \frac{\lambda}{\pi w_0}$$

$$\text{Rayleigh range: } L_R = \frac{\pi w_0^2}{\lambda}$$

$$\text{Wave length: } \lambda = \frac{\lambda_0}{n} = \frac{\lambda_{air}}{n}$$

Laser: Matrix ABCD - Focalisation of a laser beam



$$z_m = \frac{f}{1 + (f/L_{R1})^2}$$

$$w_2 = \frac{\frac{f\lambda}{\pi w_1}}{1 + (f/L_{R1})^2}$$

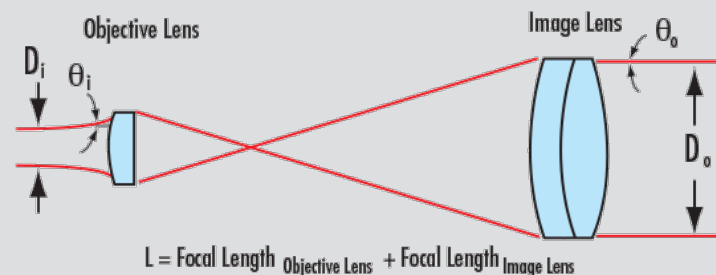
if $L_{R1} = \frac{\pi w_1^2}{\lambda} \gg f$

$$z_m \approx f$$

$$w_2 \approx \frac{f\lambda}{\pi w_1}$$

$w_1 \nearrow \Rightarrow w_2 \searrow$ smaller spot size

Beam expander to increase w_1

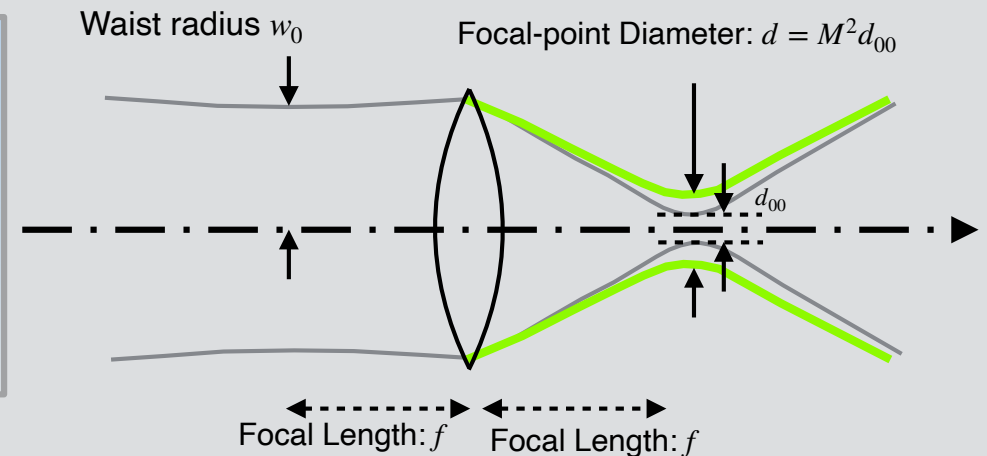


$$\frac{\theta_i}{\theta_o} = \frac{D_o}{D_i}$$

Laser: « Real » Laser Beam : M^2 Factor: beam quality factor

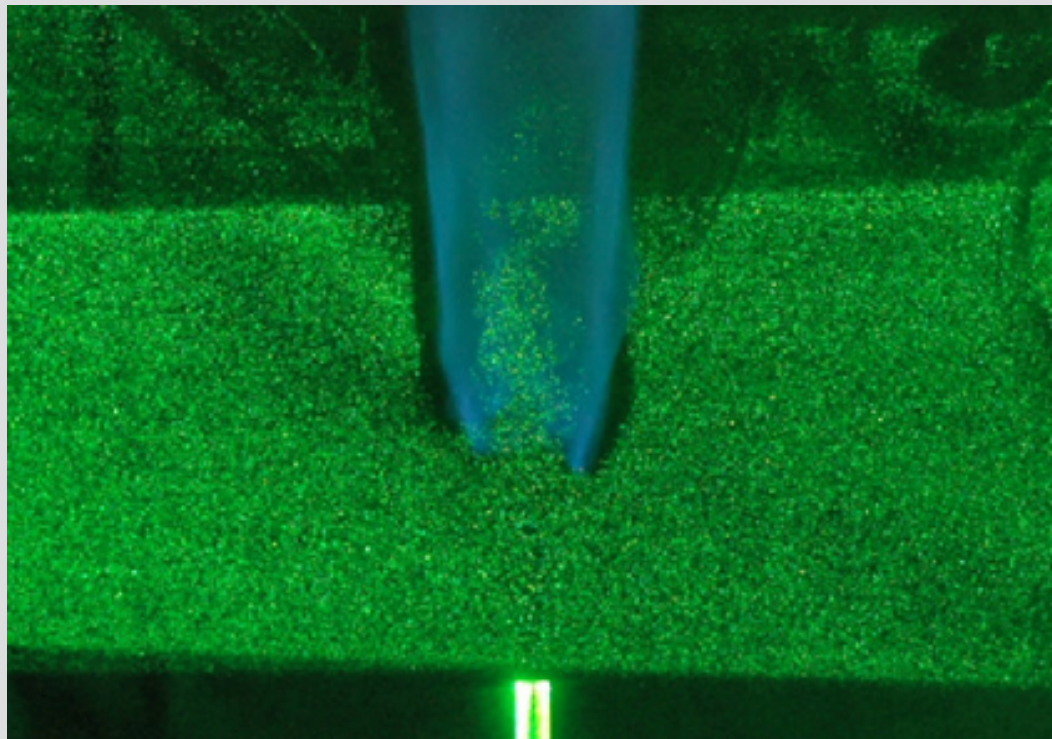
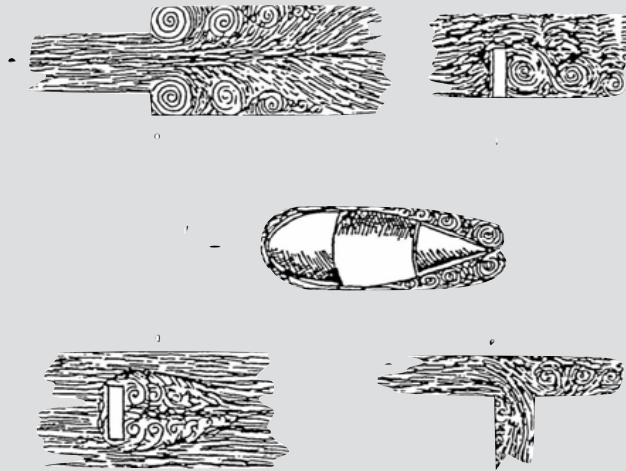
- Degree of variation of a beam from an ideal Gaussian beam
- For a single mode TEM00 (Gaussian) laser beam, M^2 is equal exactly to one
- Wavelength-independent measure of beam quality
- The diameter of the focal spot varies as M^2 (Remark : M has nothing to do with the magnification of a lens)
- Measurements can be taken with a laser beam profiler

$$\text{Divergence: } \theta = \frac{\lambda}{\pi w_0} M^2$$

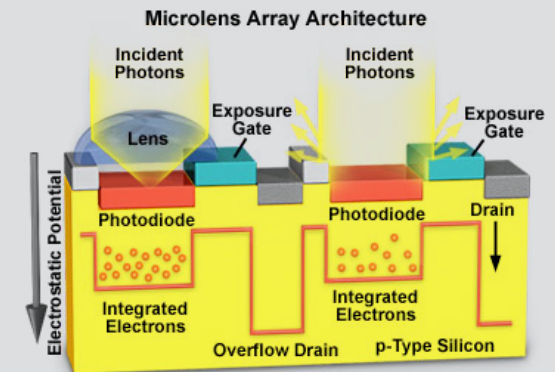
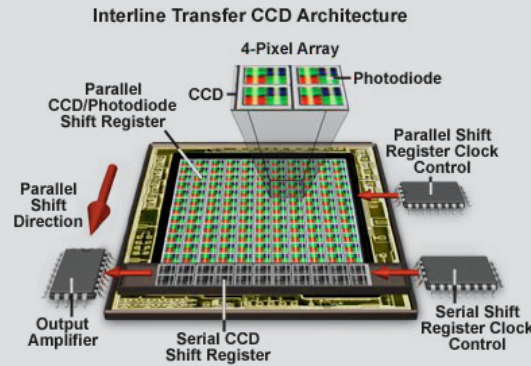


Caméra

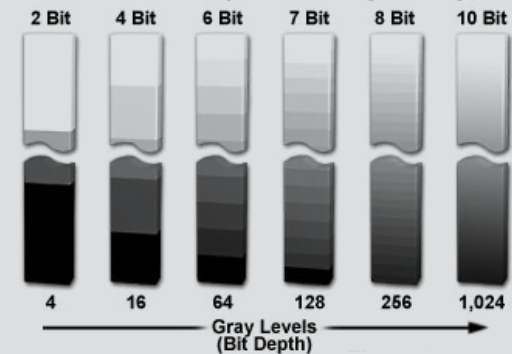
Vélocimétrie par images de particules (PIV) - Introduction



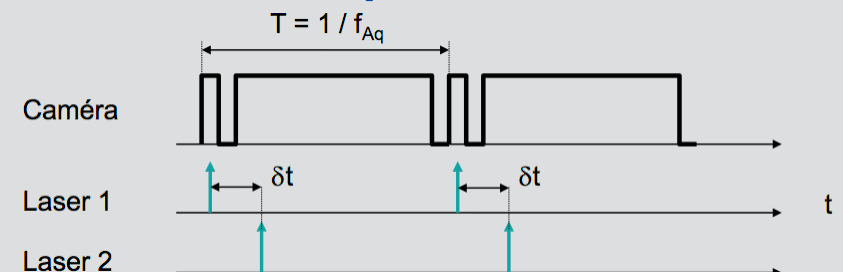
Vélocimétrie par images de particules (PIV) - Introduction



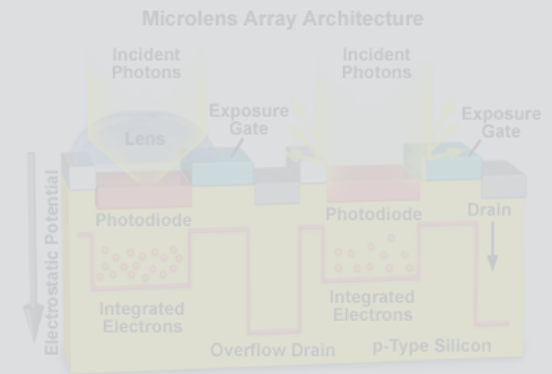
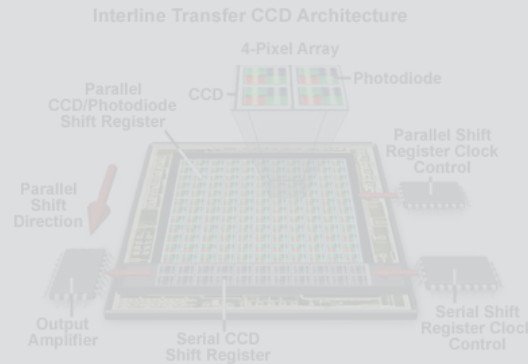
Bit Depth and Gray Levels in Digital Images



Acquisition



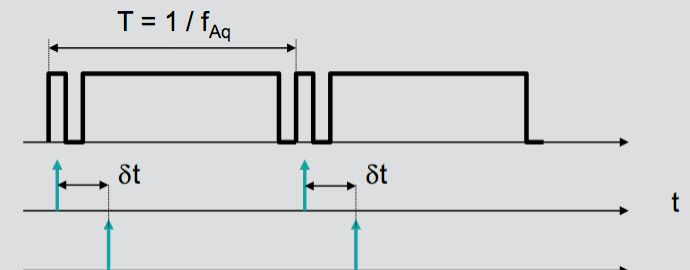
Vélocimétrie par images de particules (PIV) - Introduction



Bit Depth and Gray Levels in Digital Images



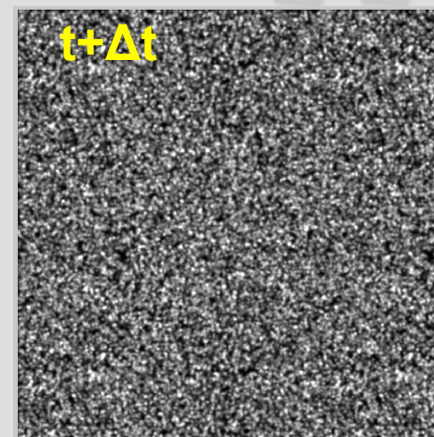
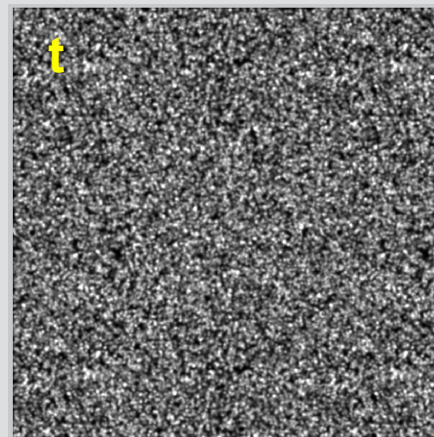
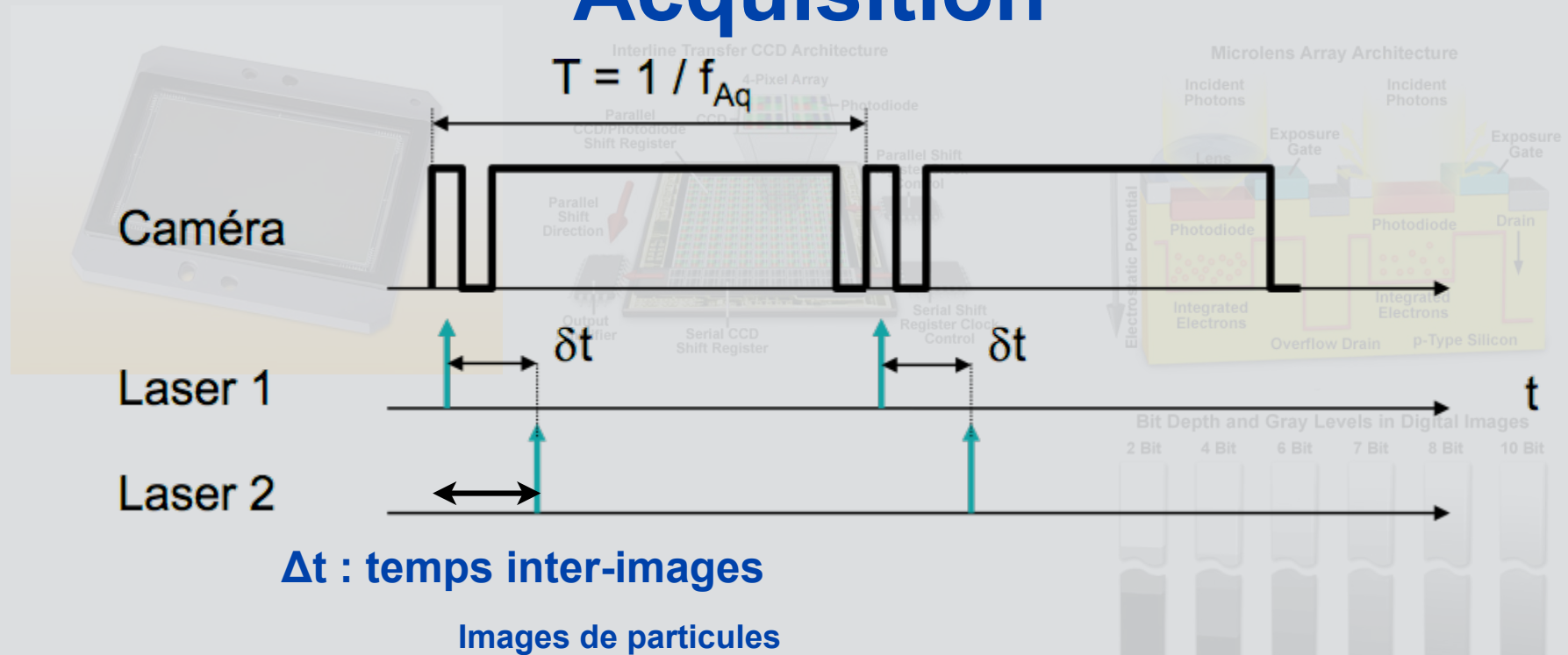
Acquisition



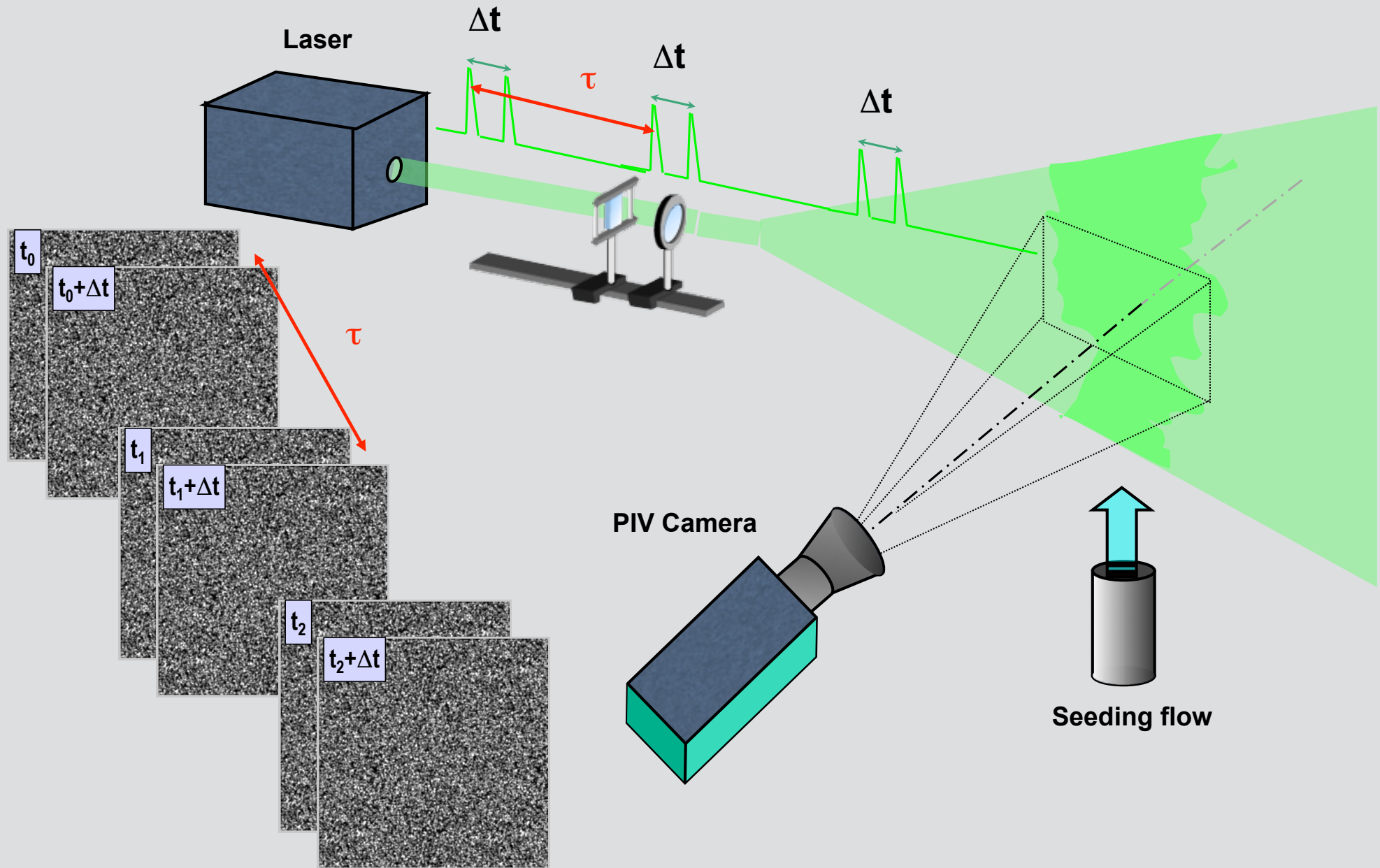
	Lavision CX3	Dantec Flowsense	Platon T2540	Phantom TMX 7510	Photron S16
					
Résolution [px]	2440 x 2040	3388 x 2712	2560x1664	1280x800	1024x1024
Pixel Size [micron]	2.7	3.35	9.27	18.5	20
Frame per Second	260	17	5 840	76 000	16000
Interframing time	200	200	250	250	200
Noise [e-]	2	3	23	24	30
Quantum Efficiency	70	52	84	78	76
Dynamic range A/D	12	14	12	12	12

Vélocimétrie par images de particules (PIV) - Introduction

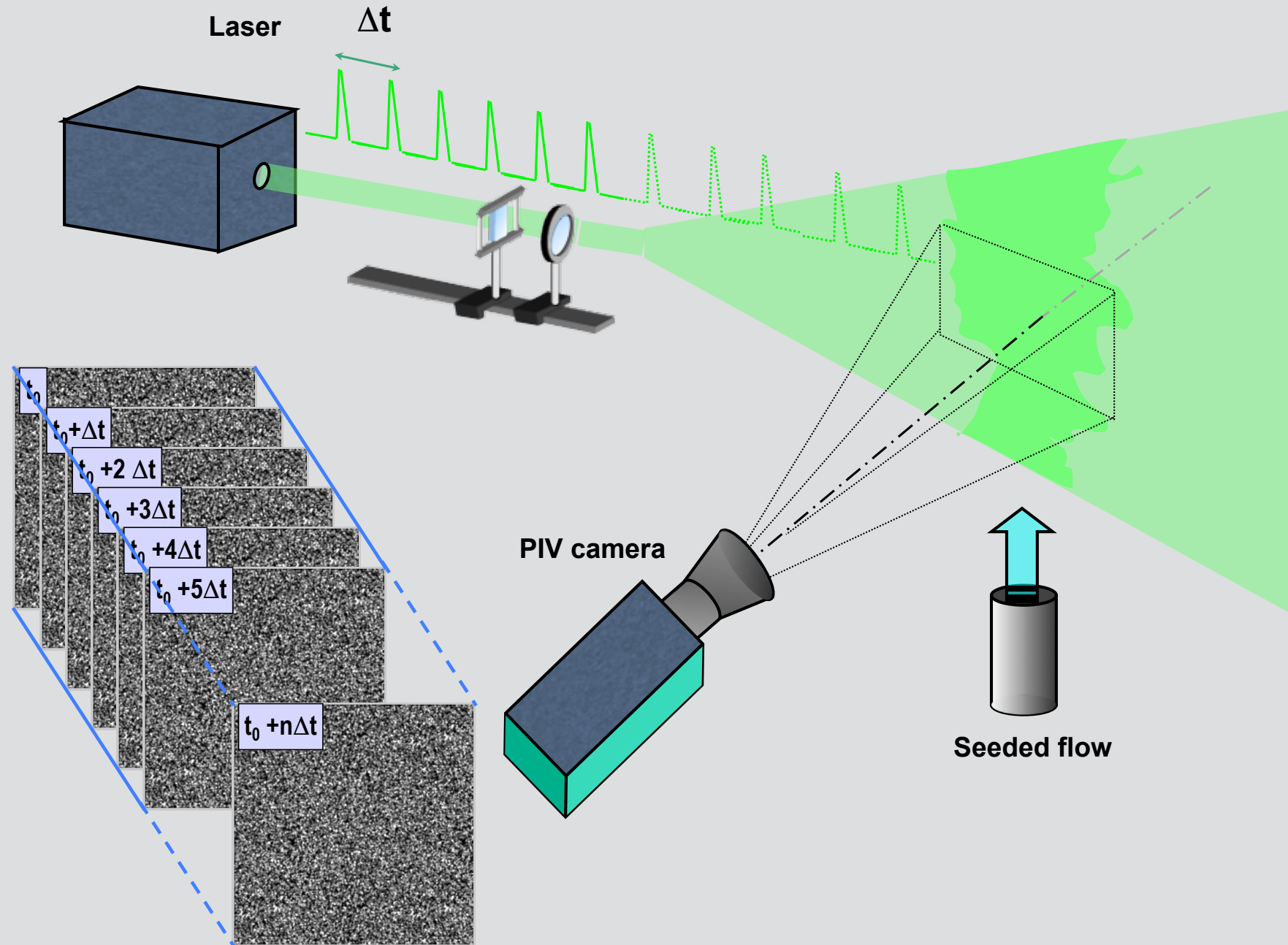
Acquisition



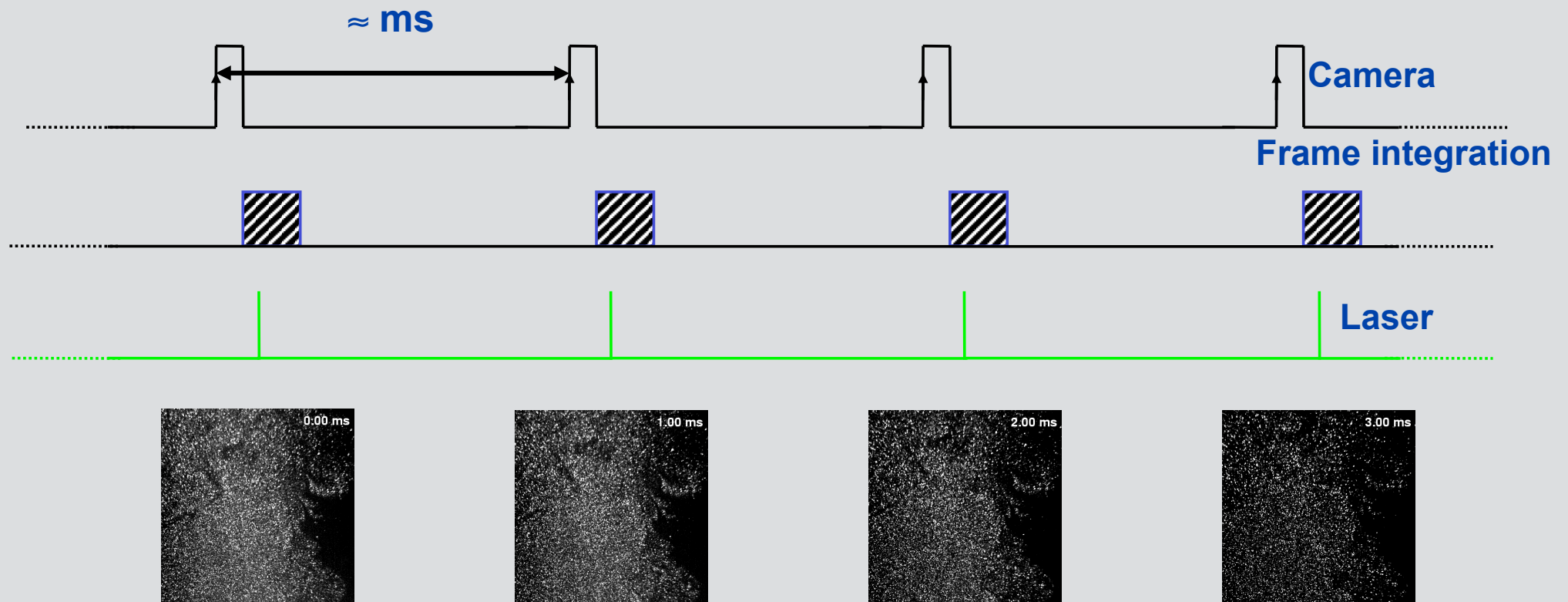
PIV recording: Acquisition timing - Frame Straddling



PIV recording: Acquisition timing



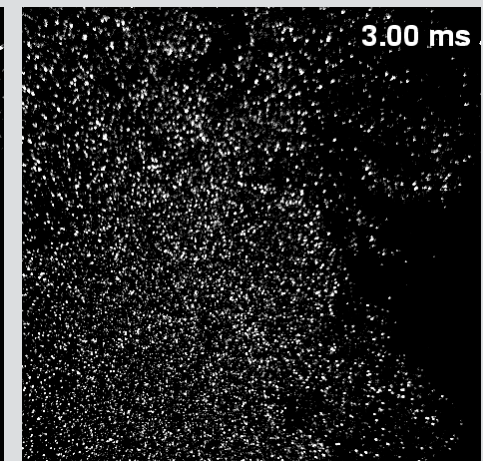
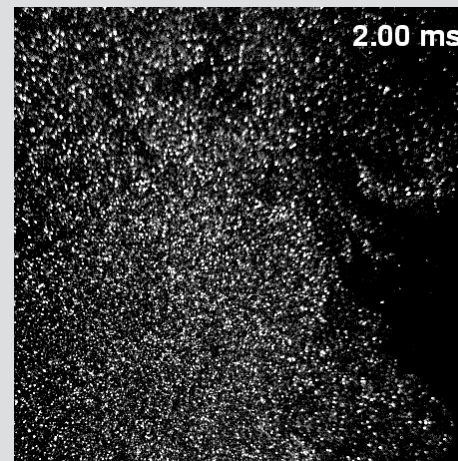
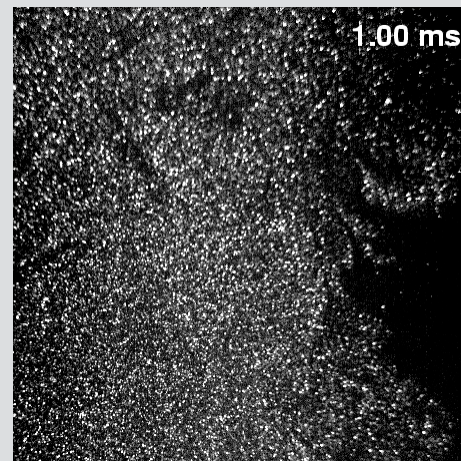
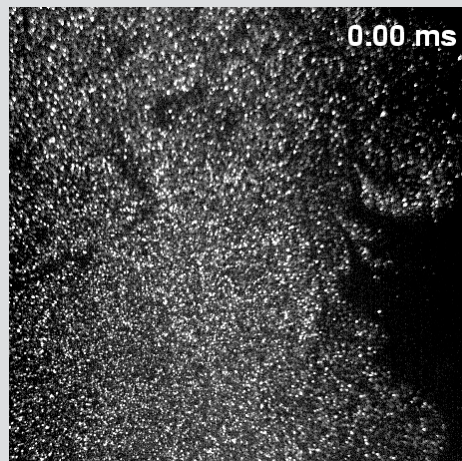
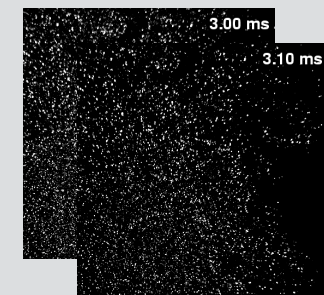
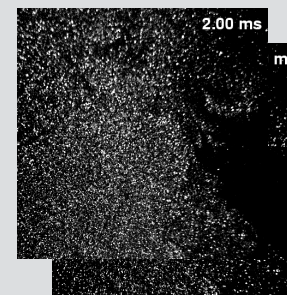
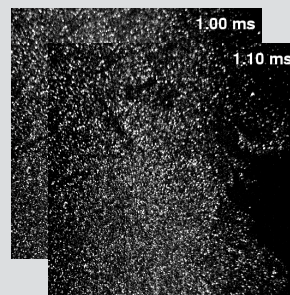
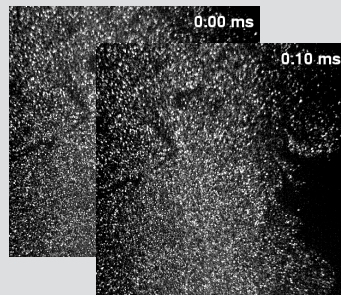
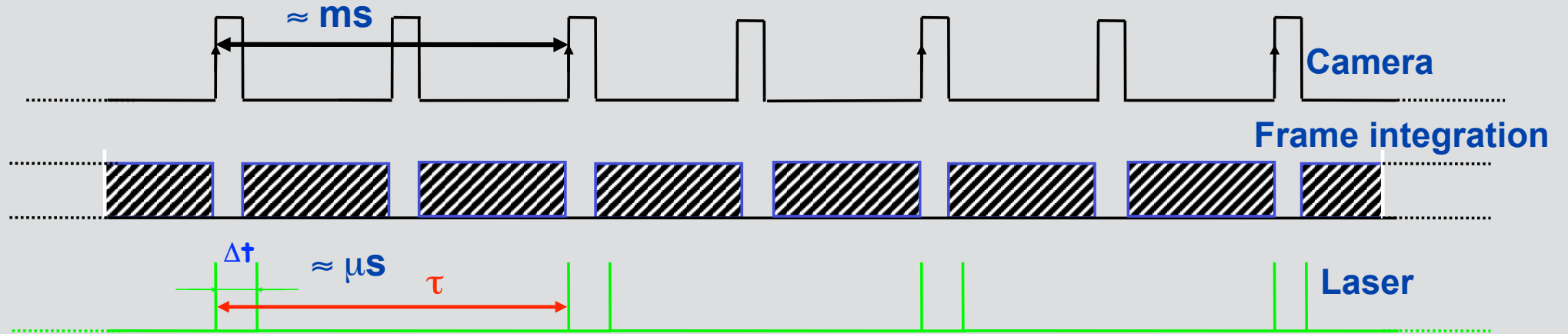
PIV recording: Acquisition timing



$$f_{camera} = f_{laser} \text{ (1 Hz to 50 kHz)}$$

$$\Delta_t = \frac{1}{f_{laser}} \text{ (1 s to } 20 \mu\text{s)}$$

PIV recording: Acquisition timing - Frame Straddling



Seeding

- Tracer particles
- Particle velocity lag
- Light scattering

Seeding: Question

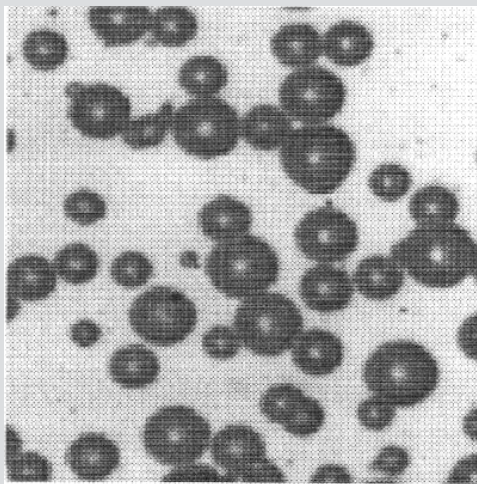
- Are the particles follow the flow ?
- How to introduce particles in the flow ?
- Can I adjust easily the particle density ?
- Is the particle size is big enough to see it on the camera ?
- Are the particles modify the flow ?
- What is the cost of particles ?
- Is the particle chemically neutral ?
- Are the particles survive to high temperature ? (ex: flame)
- Is the particle interact with the physic of the flow ? (ex: plasma)
- What about the health ?
- ...

No universal solution

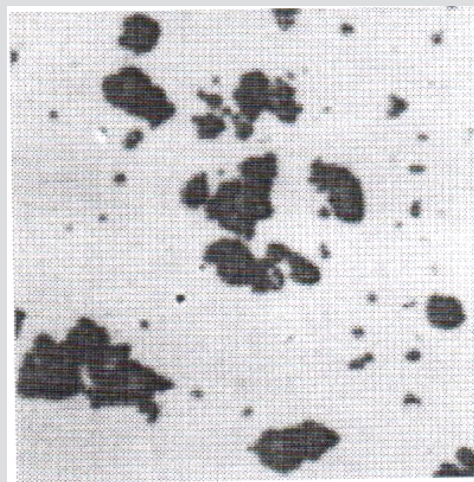
The best particles and particle generator are those adapted to your experiment

Seeding: Particles for PIV in water

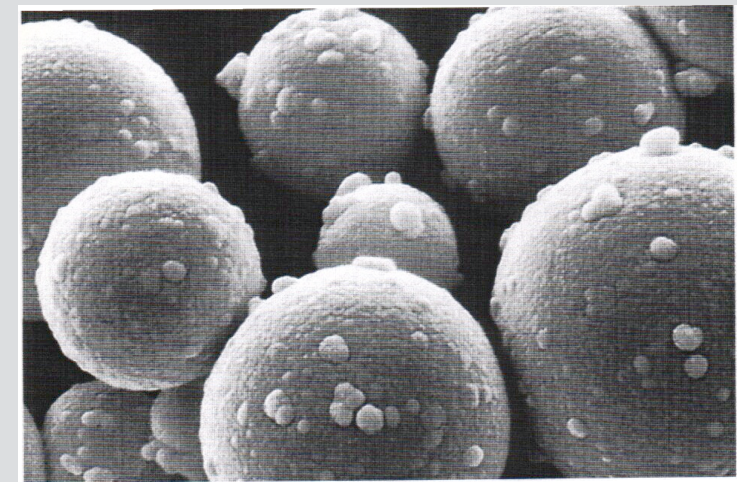
material	appr. diameter	comments	density
polystyrene latex	0.5 - 50 μm	Normal concentration: 1 part in 10^5 .	≈ 1
fluorescent polystyrene latex	0.5 - 50 μm	Feasible in close environments.	≈ 1
aluminium powder	< 10 μm	Feasible for systems demanding polarization preservation at scattering.	
plastic paint	< 10 μm	Has to be selected. A paint with too small particles cause noise.	≈ 1
bubbles	5 - 500 μm	Can only be used if two-phase flow can be accepted.	$\ll 1$



*Polystyrène $D_{mean} = 55 \mu\text{m}$,
Density = 1.02*



*Rilsan $D_{mean} = 25 \mu\text{m}$,
Density = 1.04*



*Silver-coated hollow glass spheres (S-HGS).
Enlarged 5.000 times.*

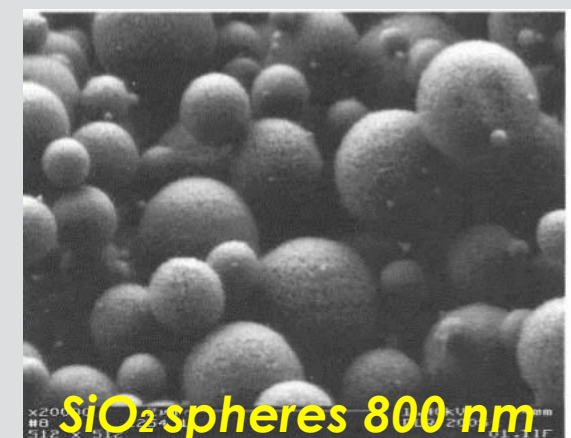
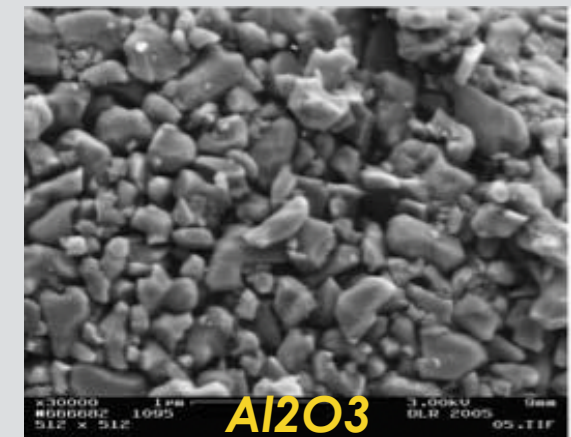
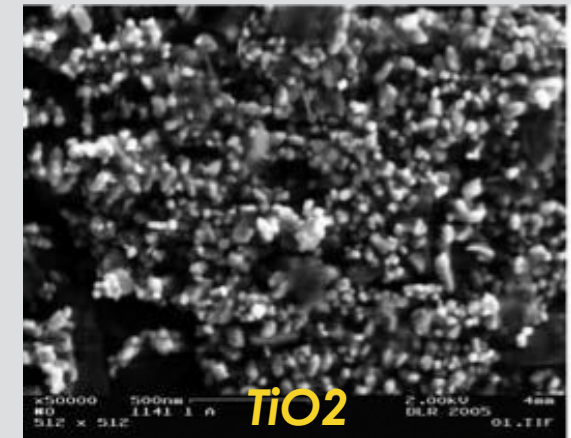
In general: Initially mixed in liquid flow with an adapted concentration for PIV

Plasmas et mécanique des fluides
17-20 nov. 2025 Saint-Etienne du Rouvray (France)

Seeding: Particles in Air

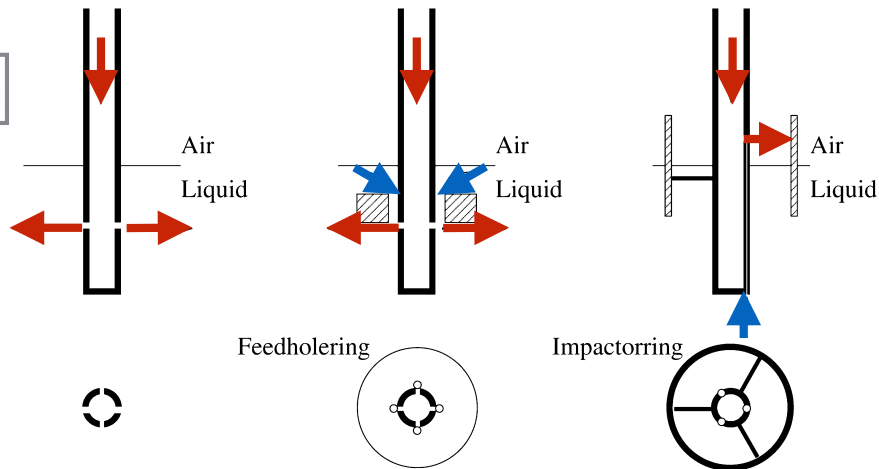
Particle	State	ρ_p (kg.m ⁻³)	d_p (μ m)
TiO ₂	Solid	3900	0.4 10
Glycol–water solution	liquid	1000	0.5 10
Glass	Solid	2600	5 100
Olive oil	Liquid	930	1 10
DEHS	Liquid	912	0.1 10
Bubble (air)		100	1 10

Particle	Density	Melting point (°C)	Boiling point (°C)
SiO ₂	2.2 to 2.6	1710	2230
TiO ₂	4.26	1640	X
Al ₂ O ₃	3.5 to 4	2050	2977
ZrO ₂	5.49	2700	4300

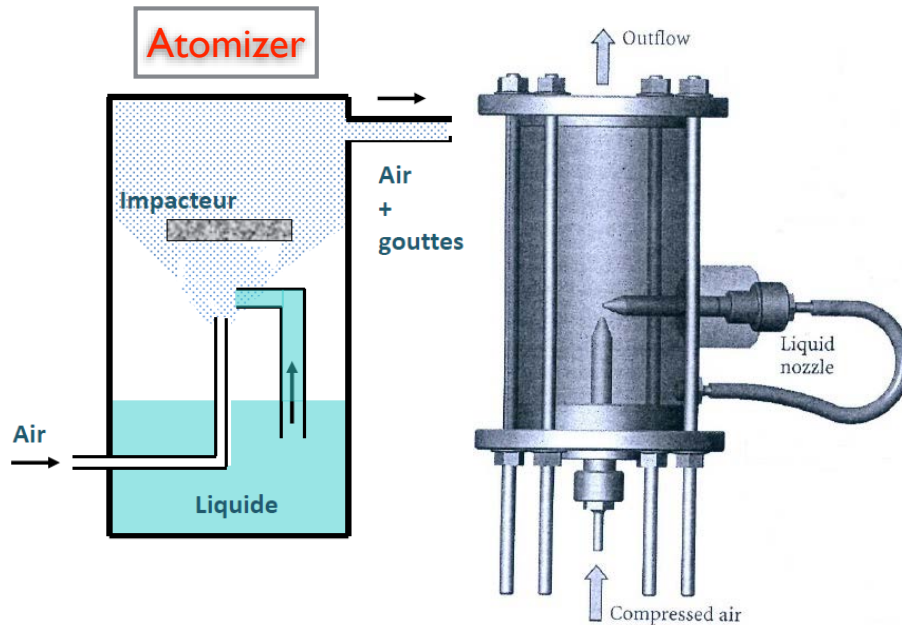


Seeding: Other seeder - Liquid Particle

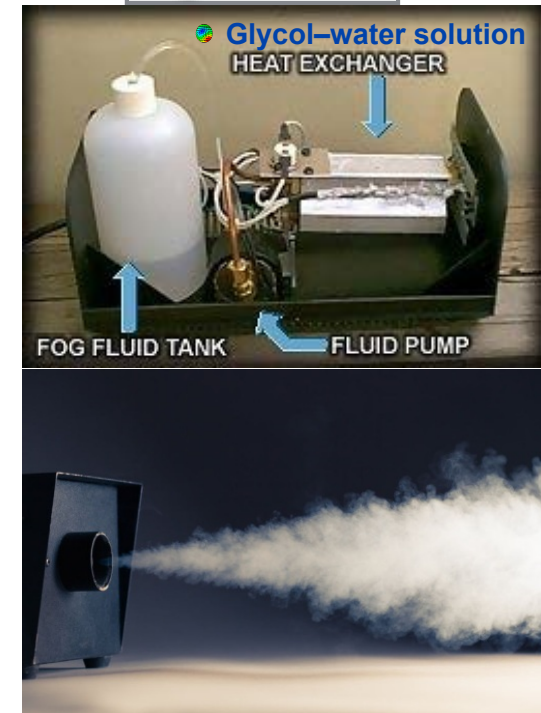
Laskin Nozzle



Atomizer

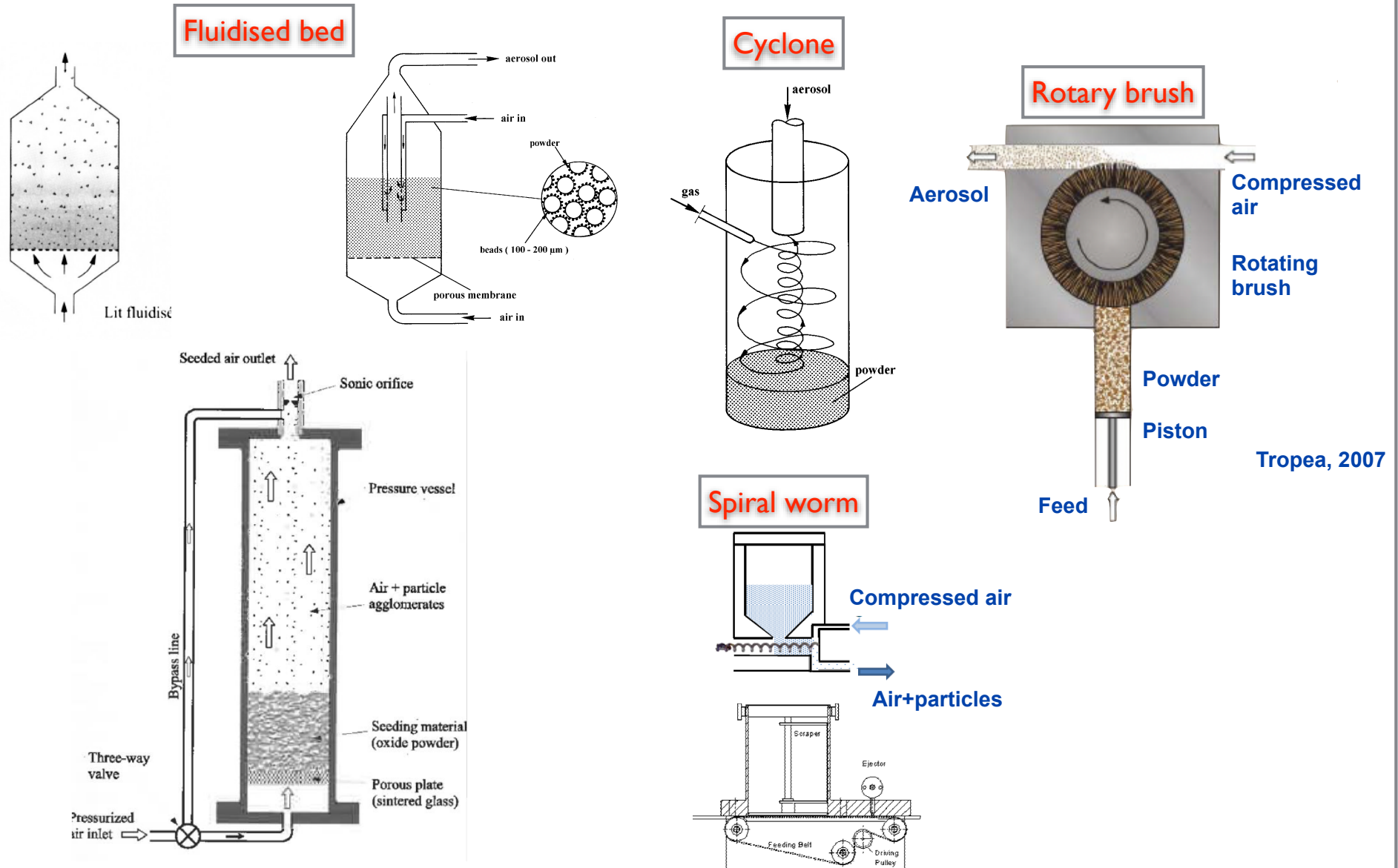


Fog Generator

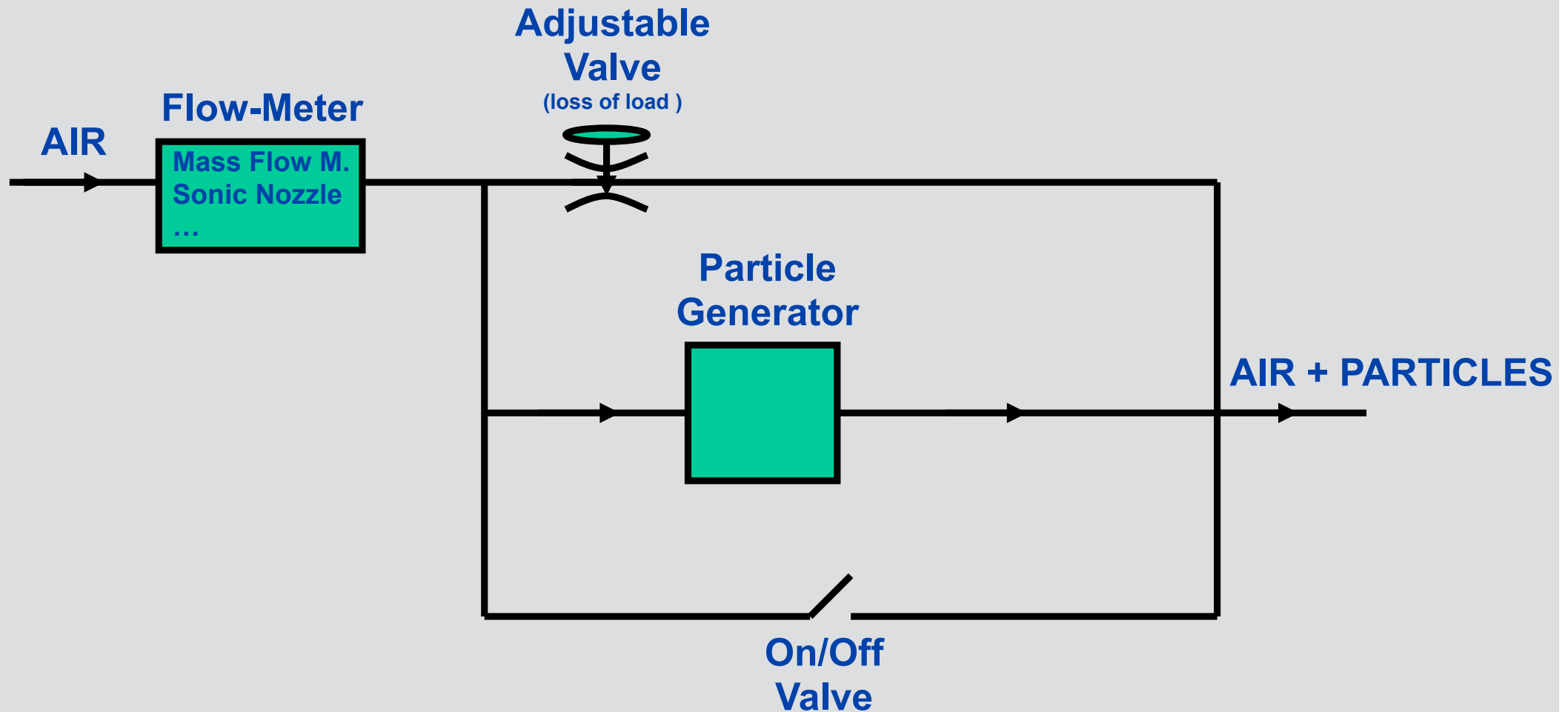


- Other possibilities :
 - Atomization (water, oil)
 - Chemical reaction (chlorides)
 - Combustion (incens, tobacco)
 - Sublimation (water)

Seeding: Other seeder - Solid Particle

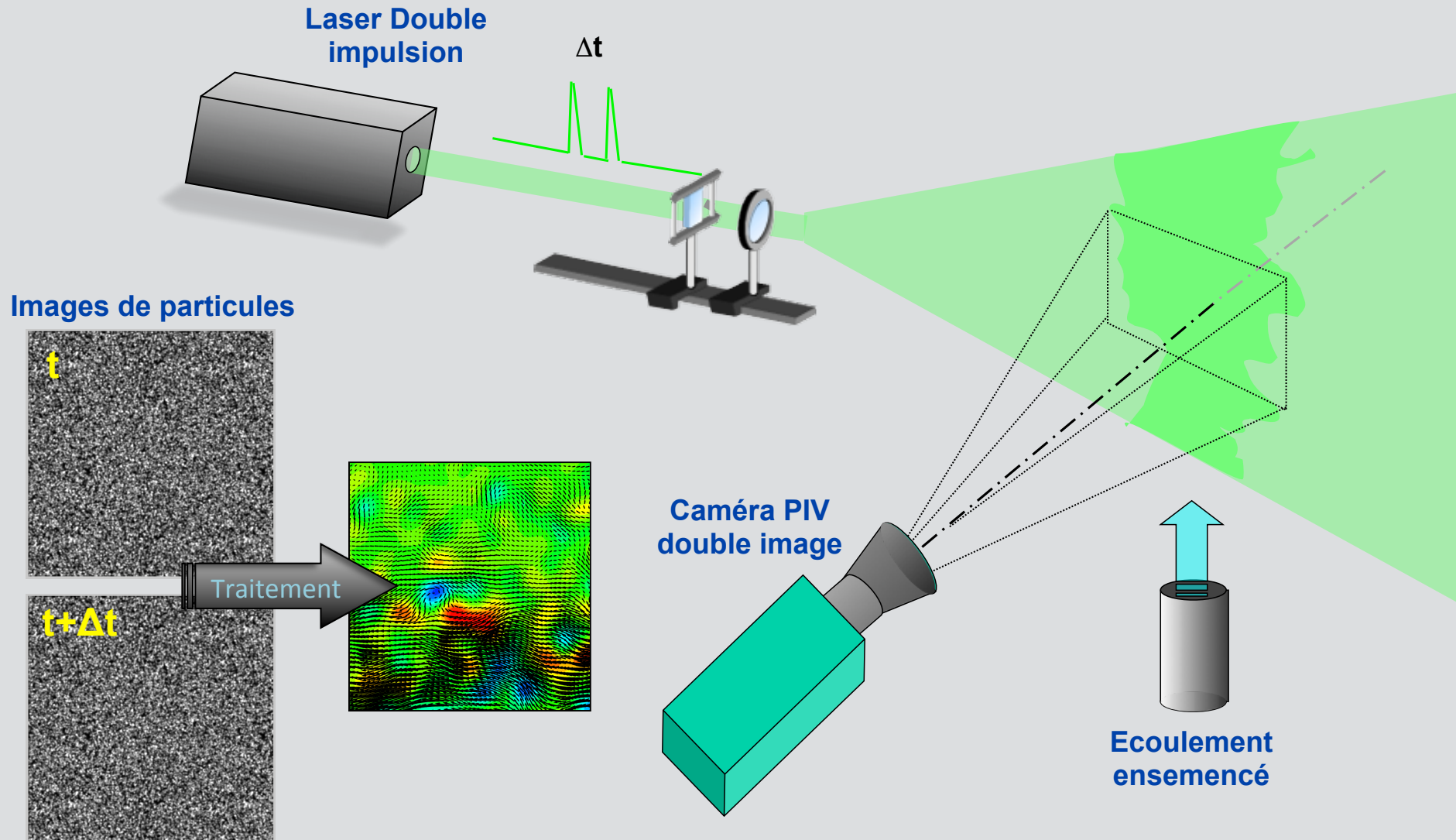


Seeder: Control the particle concentration



L'analyse des images

Vélocimétrie par images de particules (PIV) - Principe



Vélocimétrie par images de particules (PIV) - Principe

● Mesure de la vitesse locale

● Déplacement des particules :

$$\overrightarrow{\Delta x}$$

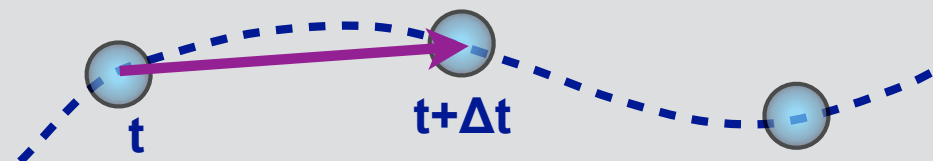
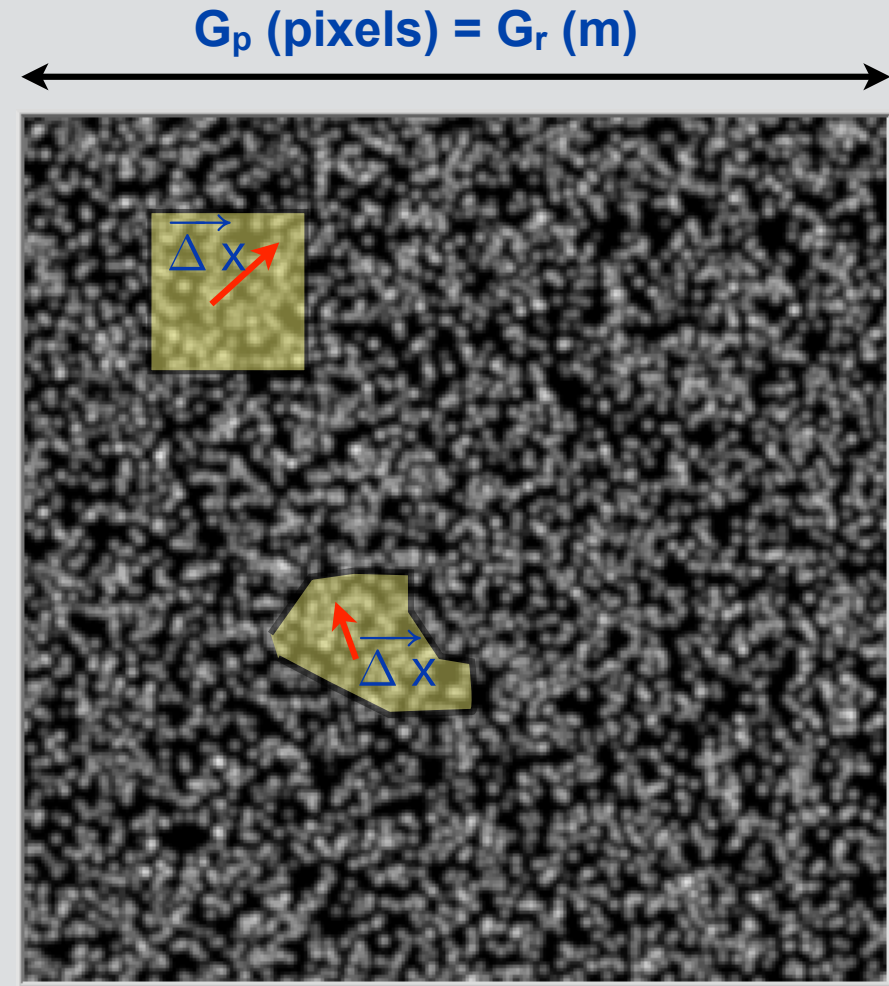
● Grandissement optique :

$$G_x = \frac{G_r}{G_p}$$

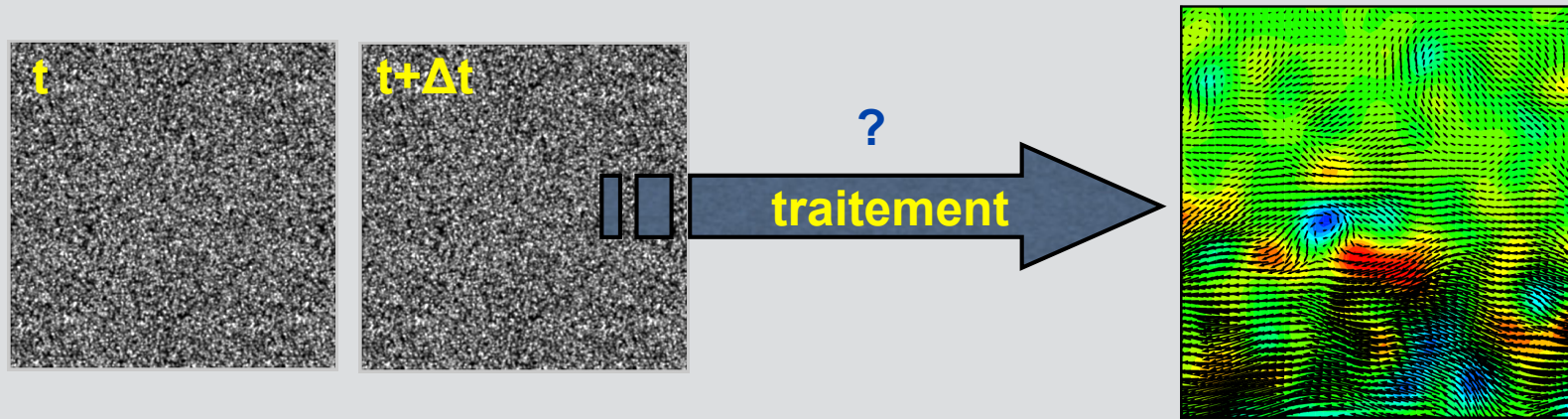
● Intervale de temps entre les laser :

$$\Delta t$$

$$\overrightarrow{u} = G_x \frac{\overrightarrow{\Delta x}}{\Delta t}$$



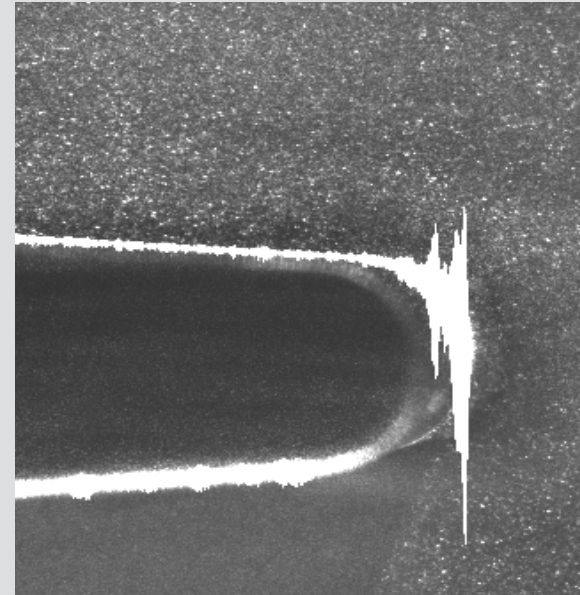
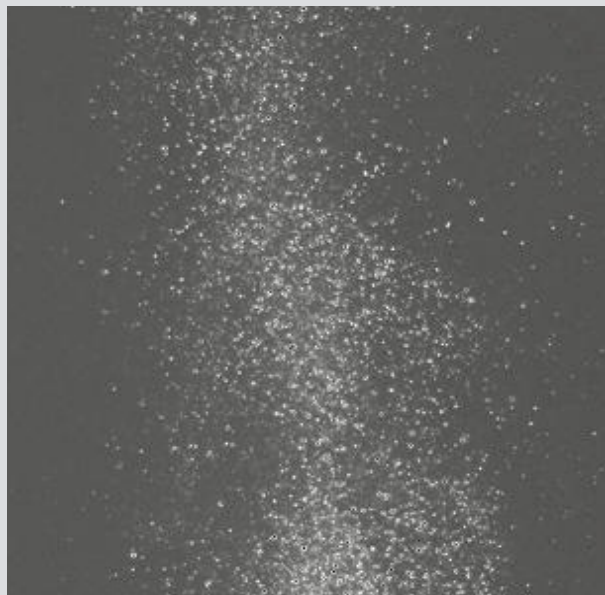
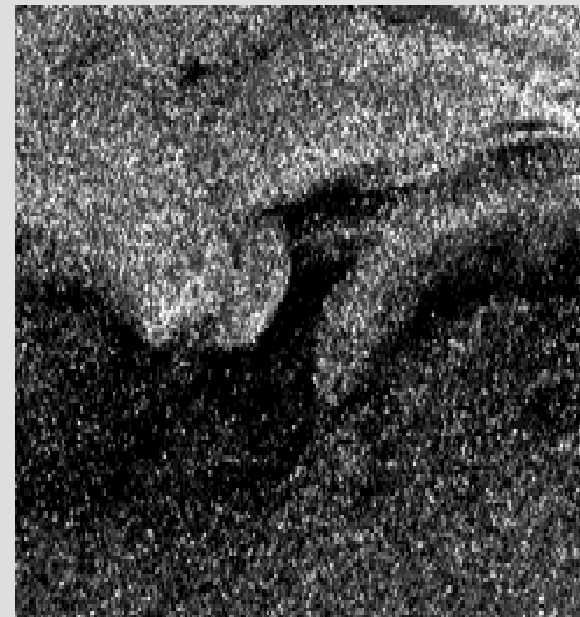
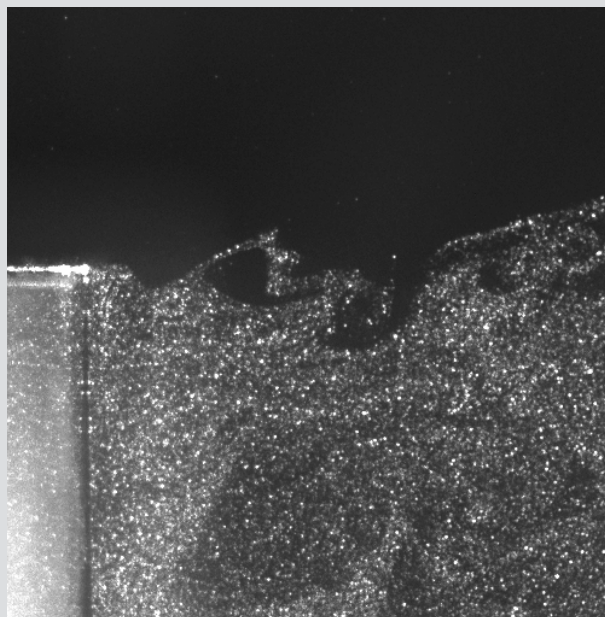
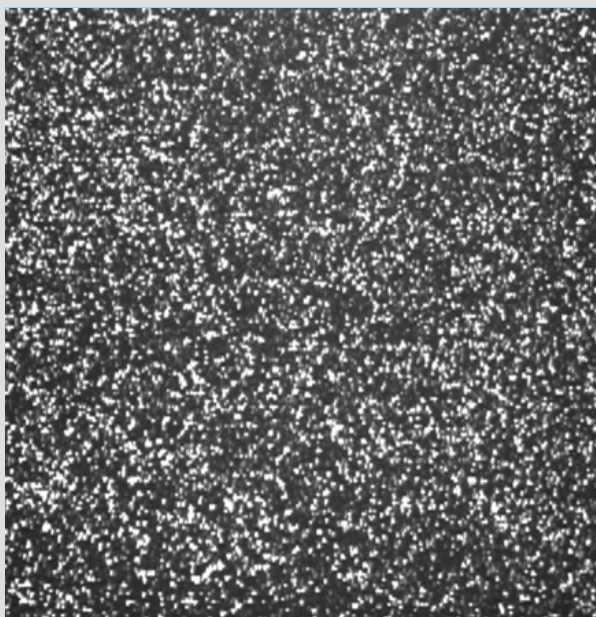
Choix de la méthode d'évaluation des vitesses



Il n'existe pas de méthode universelle pour extraire les vitesses sur les images de particules

- Choix et adaptation des méthodes aux conditions expérimentales mais également aux besoins
 - Densité et distribution de l'ensemencement
 - Bruit sur les images de particules
 - Présence d'obstacle (diffusions parasites)
 - Type des données physiques à mesurer (moyenne, fluctuation, dérivée,

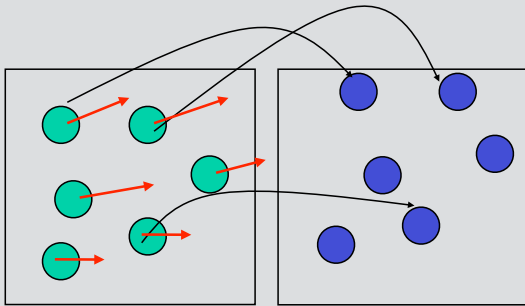
Choix de la méthode d'évaluation des vitesses : Exemples images



Deux grandes familles de méthode d'extraction des vitesses

Traitement individuel des traceurs (Particle Tracking Velocimetry - PTV)

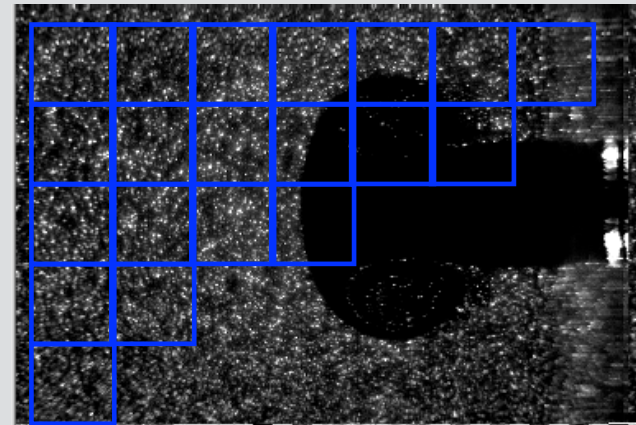
- Identification de la position des traceurs
 - Seuillage, détection de forme..
- Filtrage des particules isolées
- Appariement des particules
 - Minimisation
 - méthode neuronale
 - ...



Traitement statistique sans identification des traceurs

- Méthode par corrélation
- Méthode par minimisation
- Méthode par flot optique
- ...

☐ Zone d'analyse indépendante
de la position des traceurs



Particle Tracking Velocimetry (PTV)

- Adapté aux écoulements avec des faibles concentration en particules
- Ensemencement non uniforme (spray...)
 - Nombreux algorithmes différents pour l'identification des particules et l'appariement
- Résultat : 1 vecteur par particule identifiée
 - Résultat sur maillage non-régulier
 - Méthode de super-résolution pouvant être associée à la corrélation (Keane 1995)

OpenPTV <http://www.openptv.net/>

Open Source Particle Tracking Velocimetry

Goutte d'eau ($d \sim 40 \mu\text{m}$)



Voir : P3 - Techniques PIV Dérivées (Laurent Zimmer)

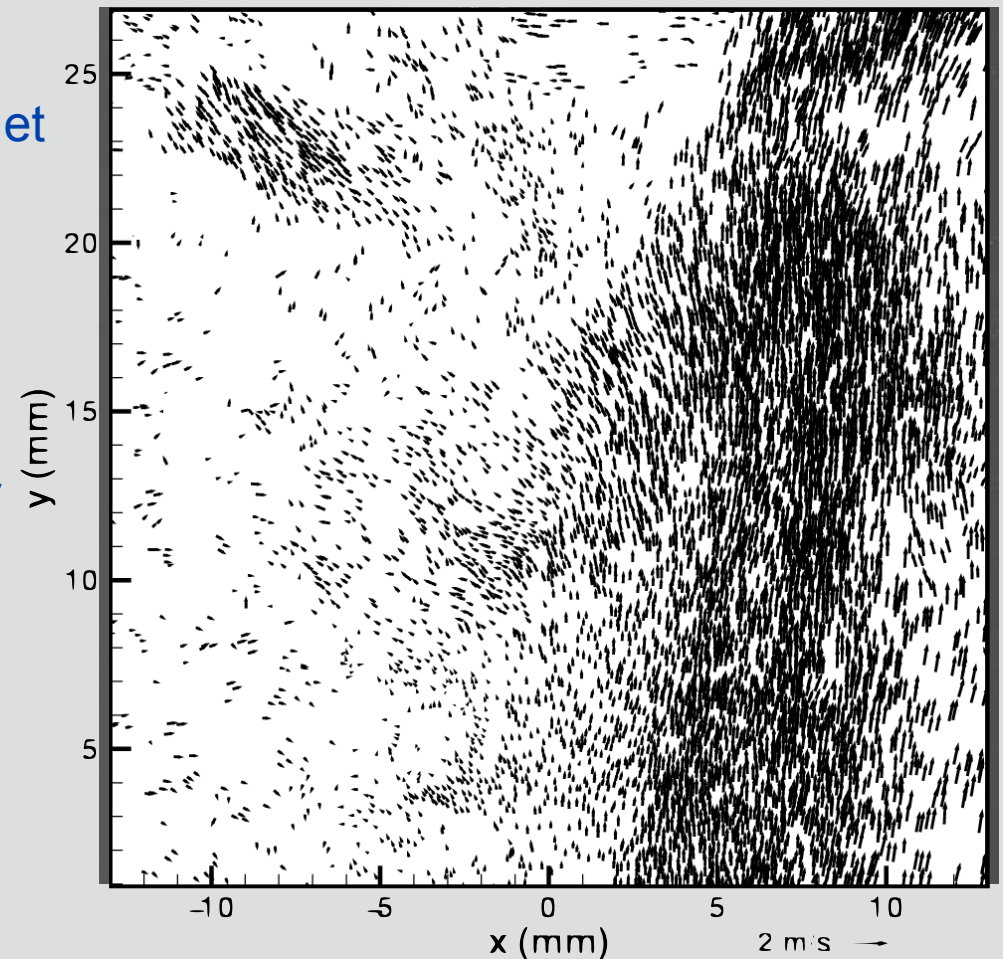
Particle Tracking Velocimetry (PTV)

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OpenPTV <http://www.openptv.net/>

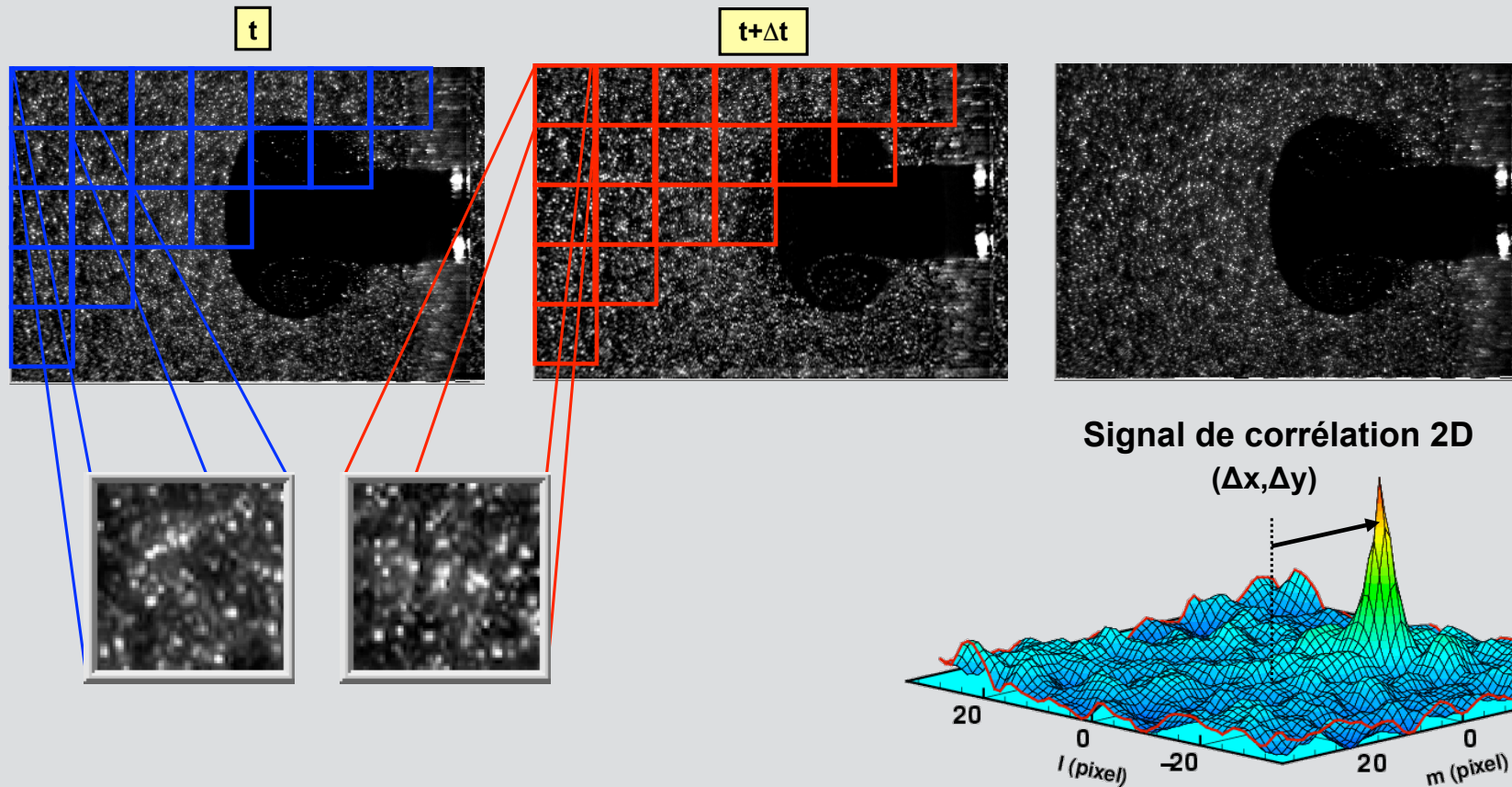
Open Source Particle Tracking Velocimetry

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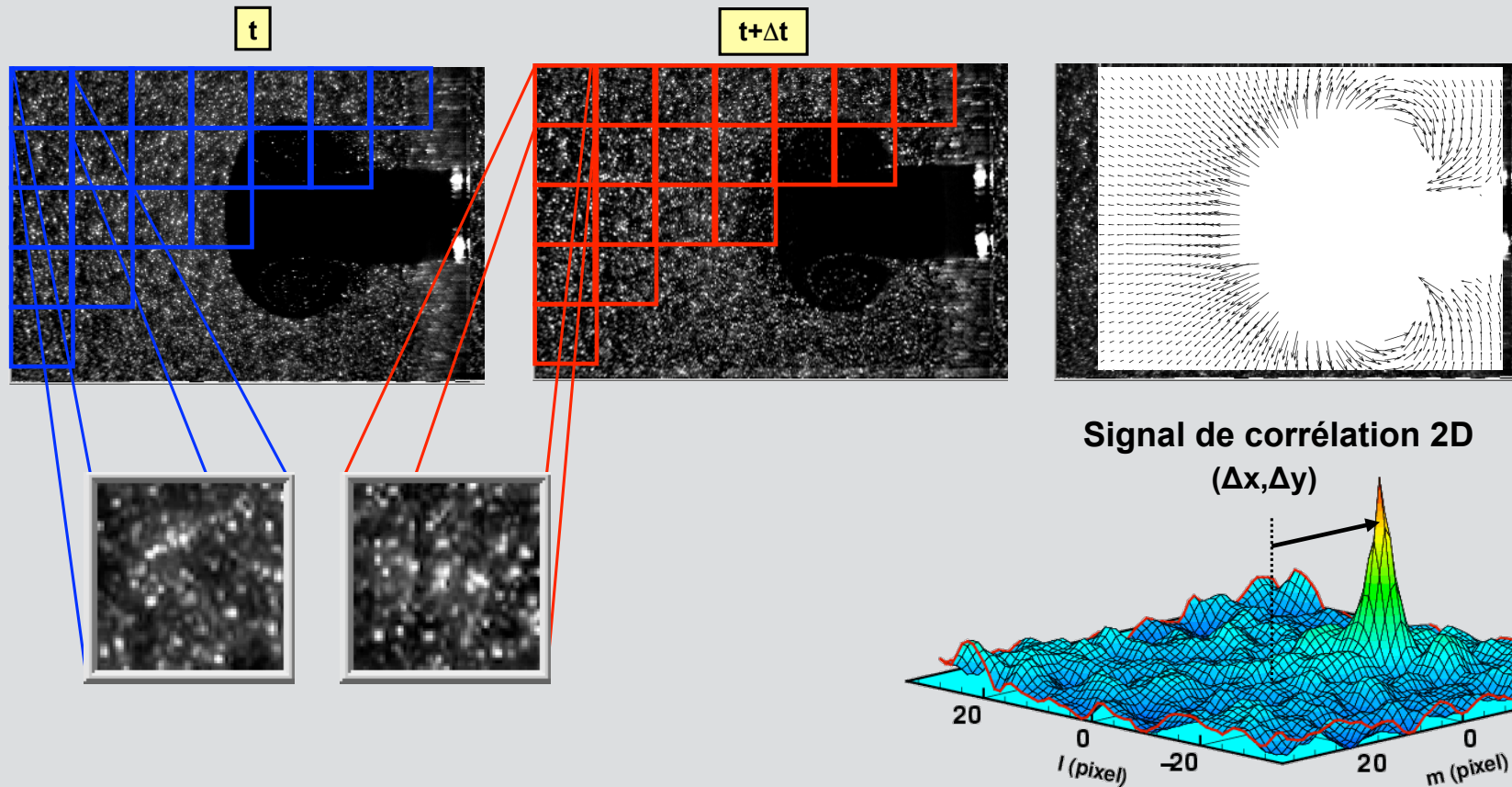
Traitement statistique des images : Corrélation croisée



$$R(m, n) = \frac{\sum_{i=-N}^{i=N} \sum_{j=-M}^{j=M} [I(i, j) - \bar{I}][J(i - m, j - n) - \bar{J}]}{\sqrt{\sigma_I^2 \sigma_J^2}}$$

Calcul numérique de la corrélation croisée
entre les mailles d'analyse

Traitement statistique des images : Corrélation croisée



$$R(m, n) = \frac{\sum_{i=-N}^{i=N} \sum_{j=-M}^{j=M} [I(i, j) - \bar{I}][J(i - m, j - n) - \bar{J}]}{\sqrt{\sigma_I^2 \sigma_J^2}}$$

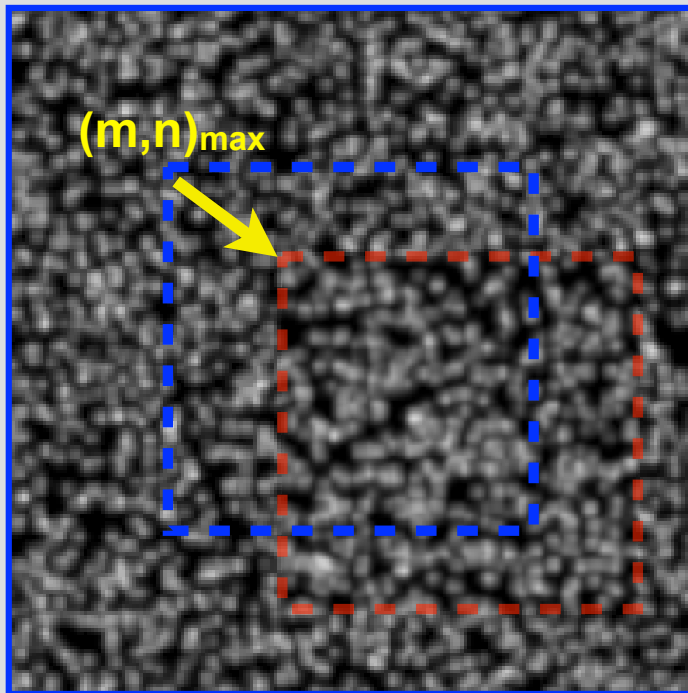
Calcul numérique de la corrélation croisée
entre les mailles d'analyse

Traitement des images par corrélation croisée : Principe

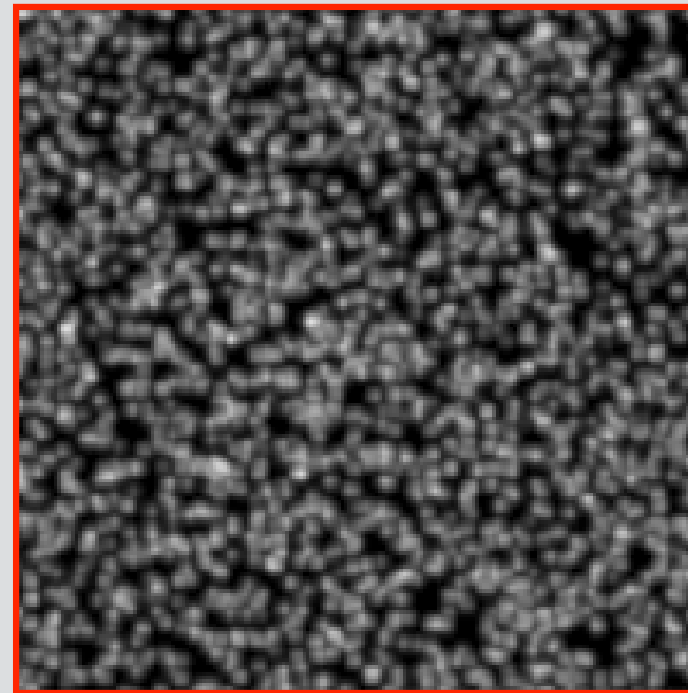
$$R(m,n) = \frac{\sum_{i=-N}^{i=N} \sum_{j=-M}^{j=M} [I(i,j) - \bar{I}][J(i-\boxed{m}, j-\boxed{n}) - \bar{J}]}{\sqrt{\sigma_I^2 \sigma_J^2}}$$

Rechercher (m, n)
pour maximiser
R(m,n)

I(i,j)

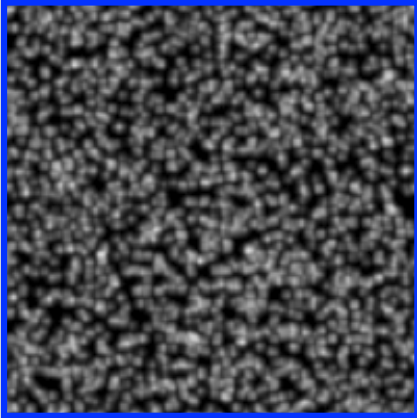


J(i,j)

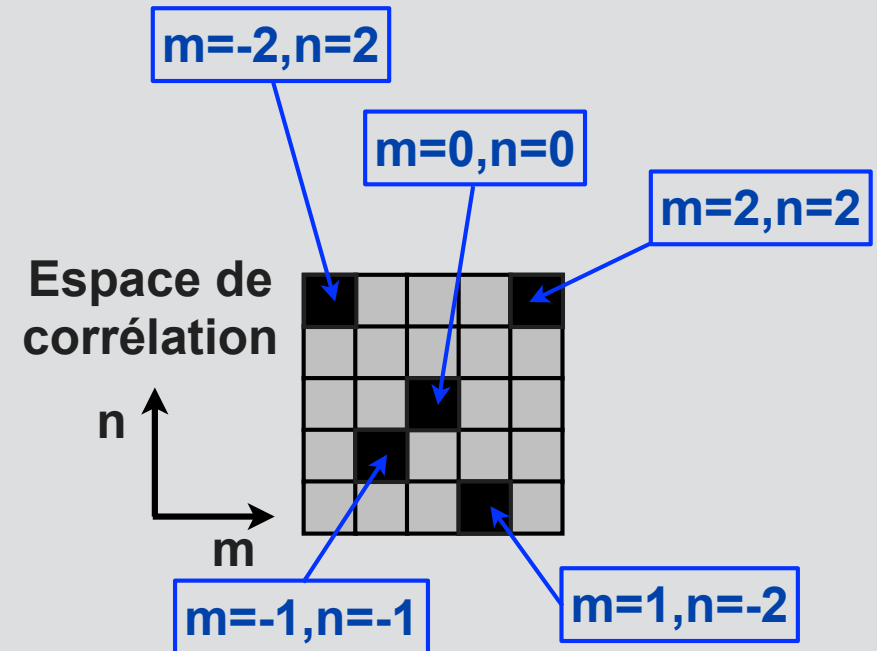
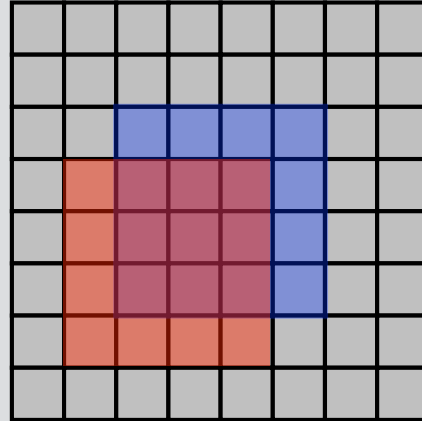
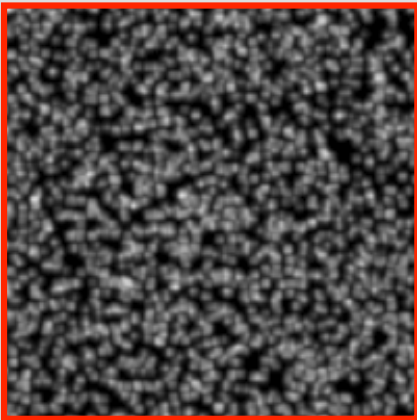


Traitement des images par corrélation croisée : Principe

$I(i,j)$



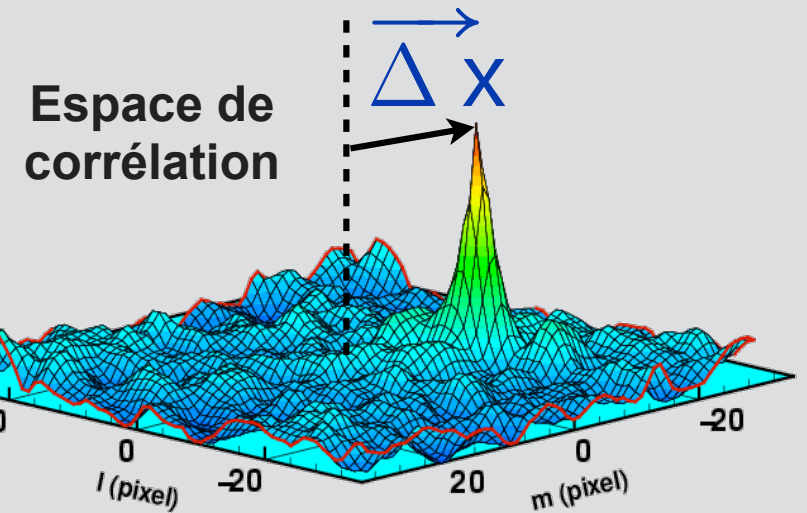
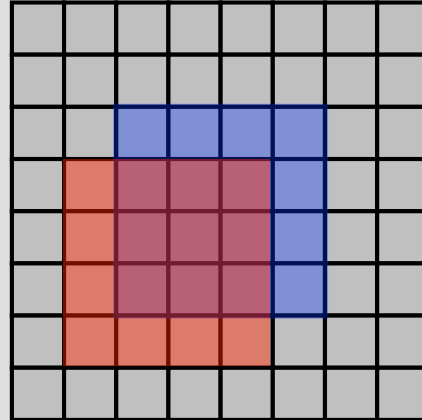
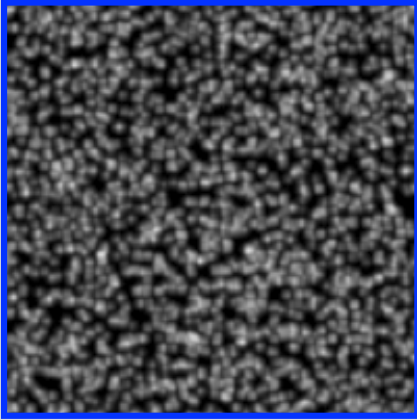
$J(i,j)$



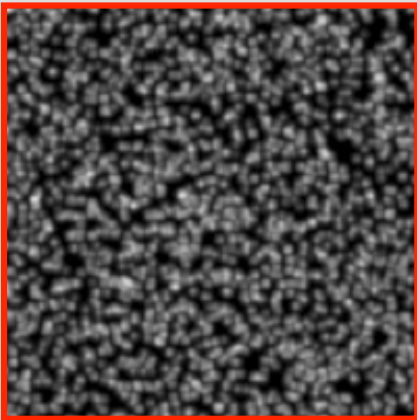
$$R(m,n) = \frac{\sum_{i=-N}^{i=N} \sum_{j=-M}^{j=M} [I(i,j) - \bar{I}][J(i-m, j-n) - \bar{J}]}{\sqrt{\sigma_I^2 \sigma_J^2}}$$

Traitement des images par corrélation croisée : Principe

$I(i,j)$



$J(i,j)$



$$\vec{u} = G_x \frac{\vec{\Delta x}}{\Delta t}$$

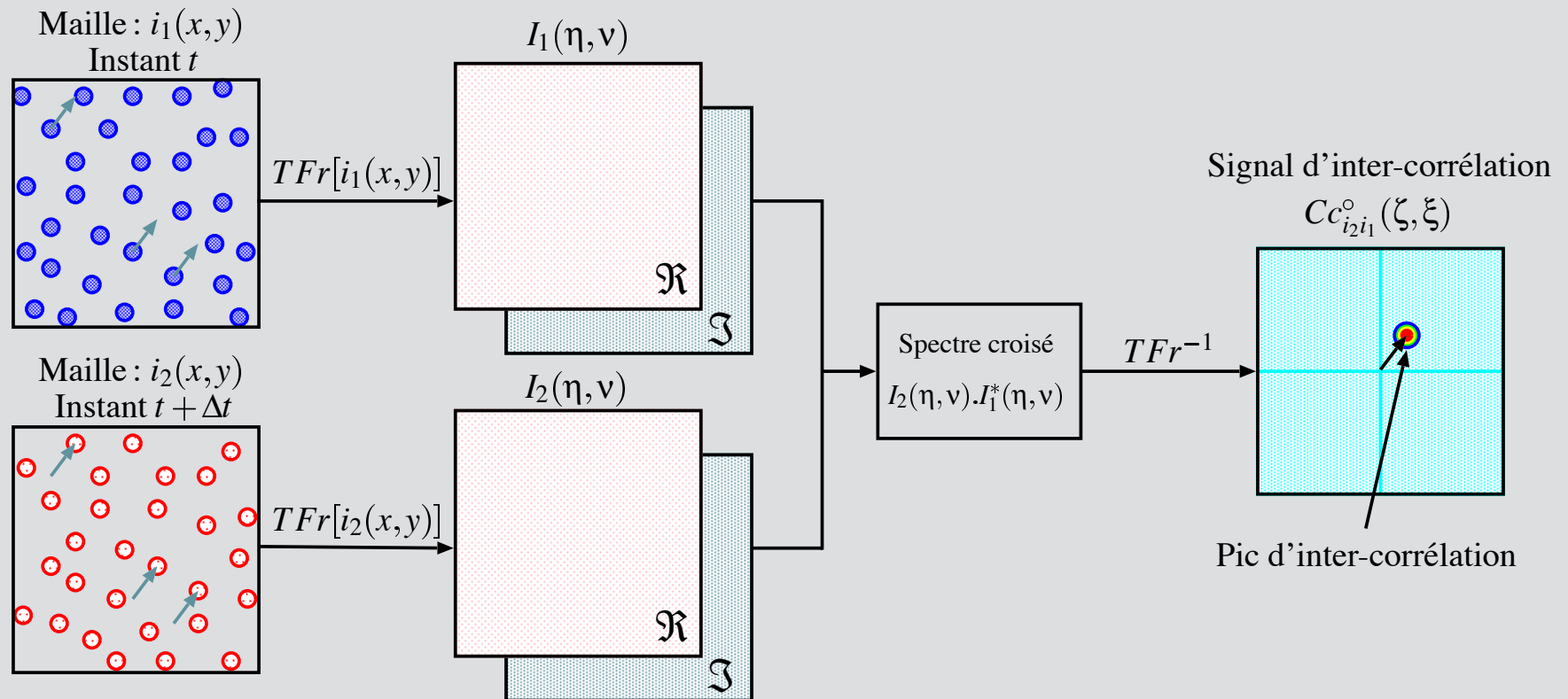
$$R(m,n) = \frac{\sum_{i=-N}^{i=N} \sum_{j=-M}^{j=M} [I(i,j) - \bar{I}][J(i-m, j-n) - \bar{J}]}{\sqrt{\sigma_I^2 \sigma_J^2}}$$

Calcul rapide de la corrélation par transformation de Fourier

$$R(m,n) = \frac{\sum_{i=-N}^{i=N} \sum_{j=-M}^{j=M} [I(i,j) - \bar{I}][J(i-m,j-n) - \bar{J}]}{\sqrt{\sigma_I^2 \sigma_J^2}}$$

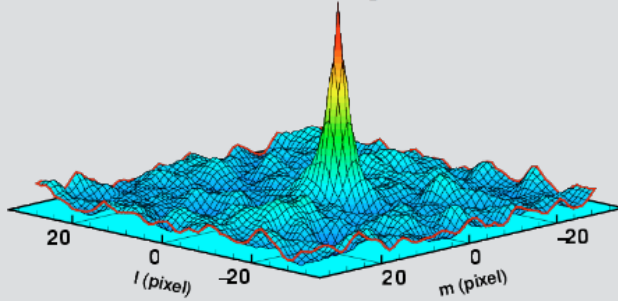
théorème de Wiener - Khintchine

$$Cc_{fg}(\vec{\chi}) \rightleftharpoons F(\vec{\mu})G^*(\vec{\mu})$$

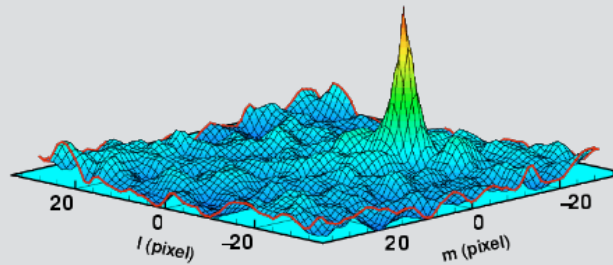


Exemples de signaux de corrélation pour 3 vitesses

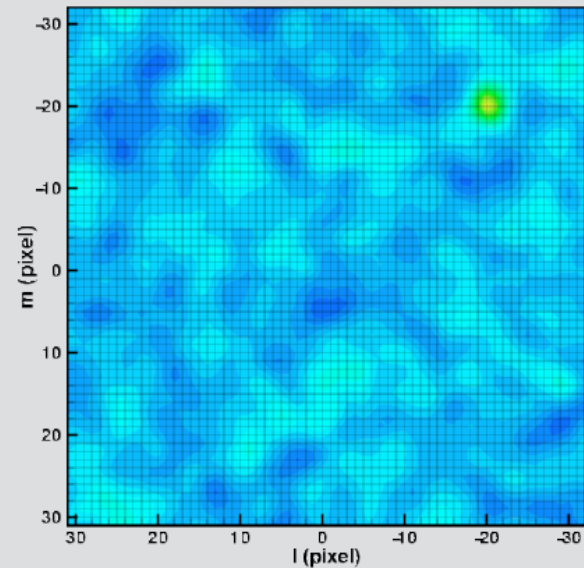
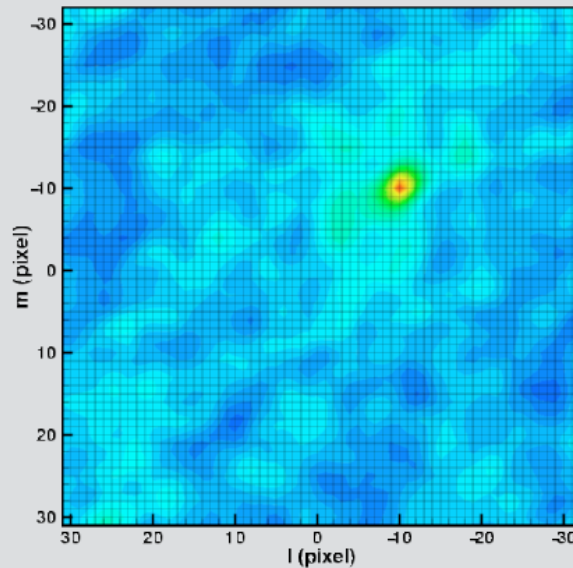
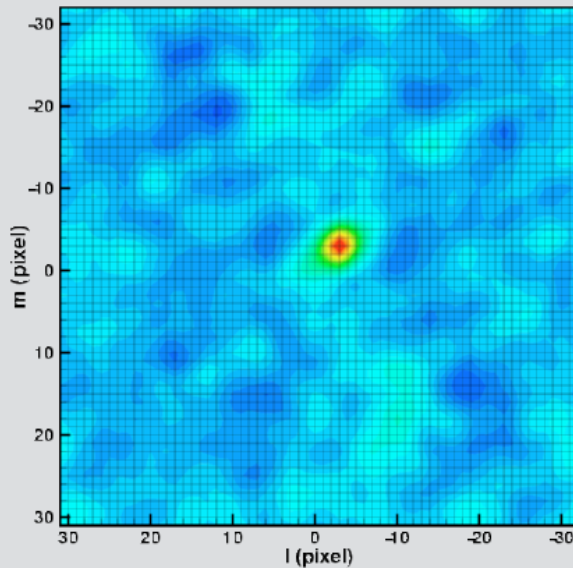
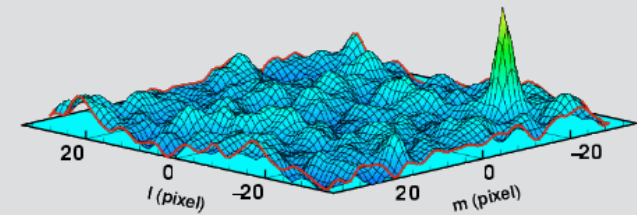
$u \sim v \sim 3$ pixels



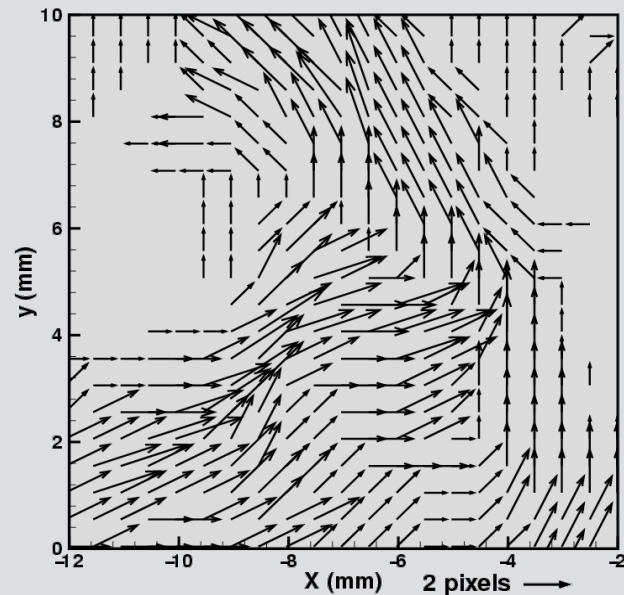
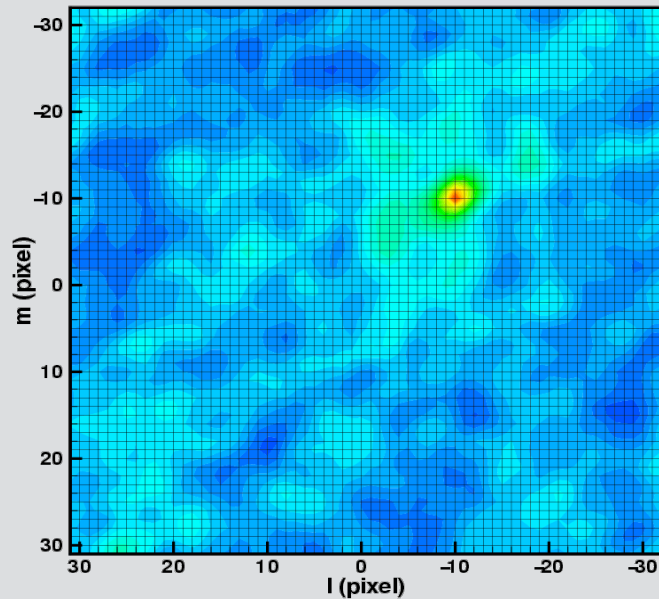
$u \sim v \sim 10$ pixels



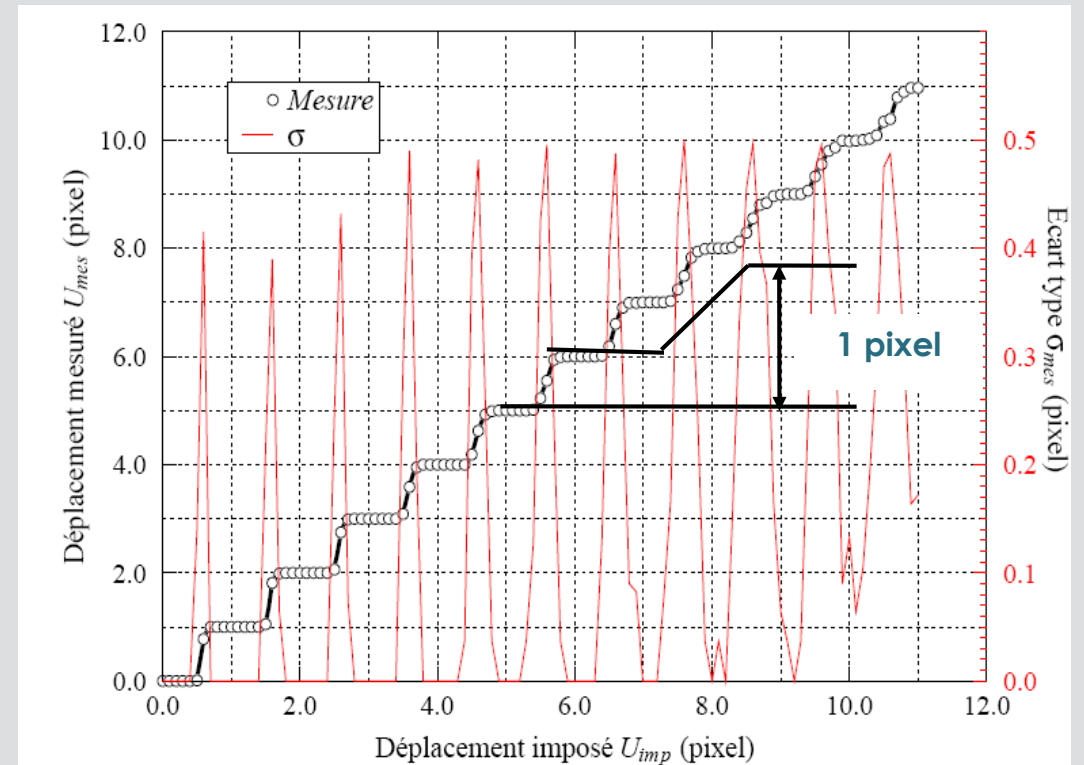
$u \sim v \sim 20$ pixels



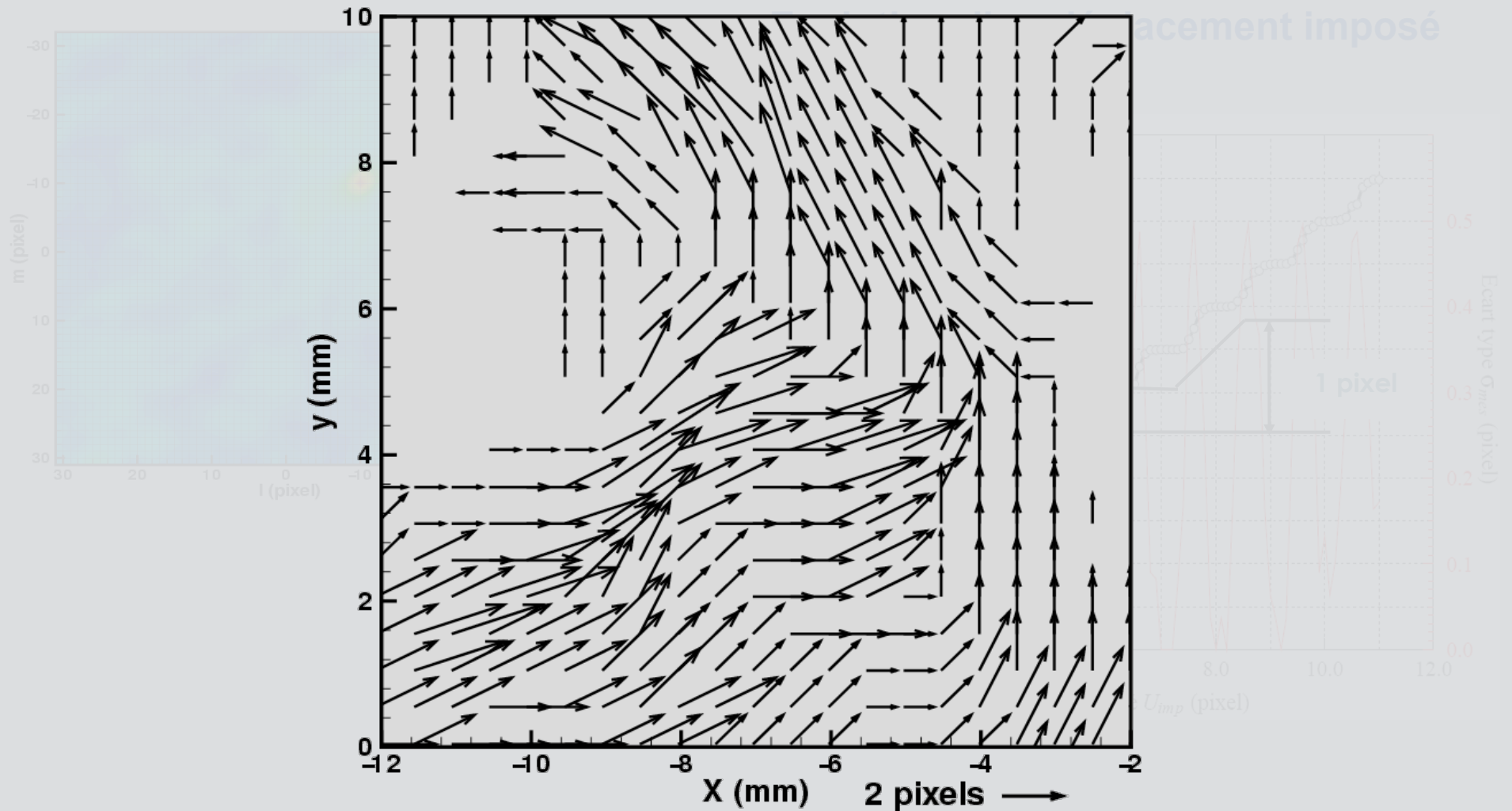
Effet de l'échantillonnage de la corrélation sur la mesure



Evolution d'un déplacement imposé

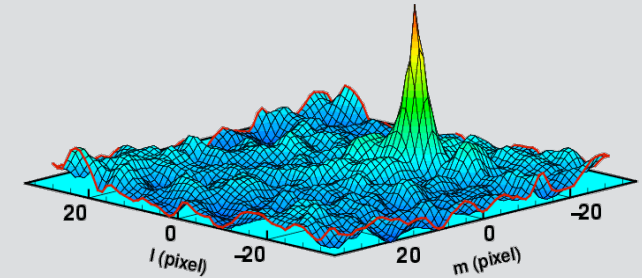


Effet de l'échantillonnage de la corrélation sur la mesure



Principe du sub-pixel 1/4

● Vitesse : Position du maximum de corrélation



- Corrélation calculée sur un maillage : valeurs possibles $\sim IW \text{ Size}/2$

- Erreur sur la mesure ± 0.5 pixel

● Position et forme de l'enveloppe du pic $\rightarrow$ Méthodes Sub-pixel

- La forme de l'enveloppe du pic de corrélation provient de la corrélation de plusieurs particules positionnées aléatoirement dans la fenêtre d'interrogation. Elle contient alors une information sur le déplacement.

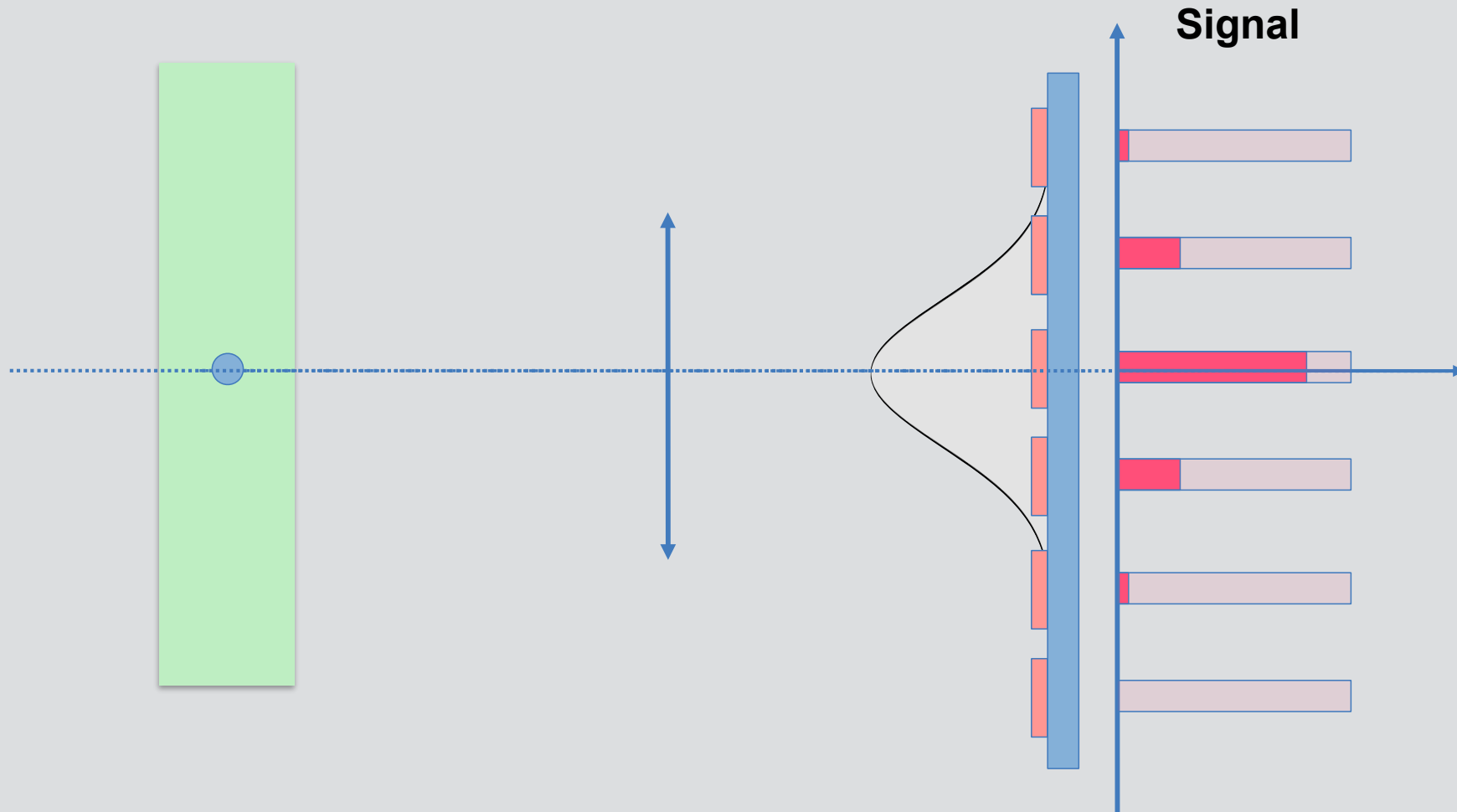
● Précision sub-pixel

- De l'ordre de $1/10$ à $1/20$ de pixel

Enregistrement du déplacement d'une particule

Principe du sub-pixel 2/4

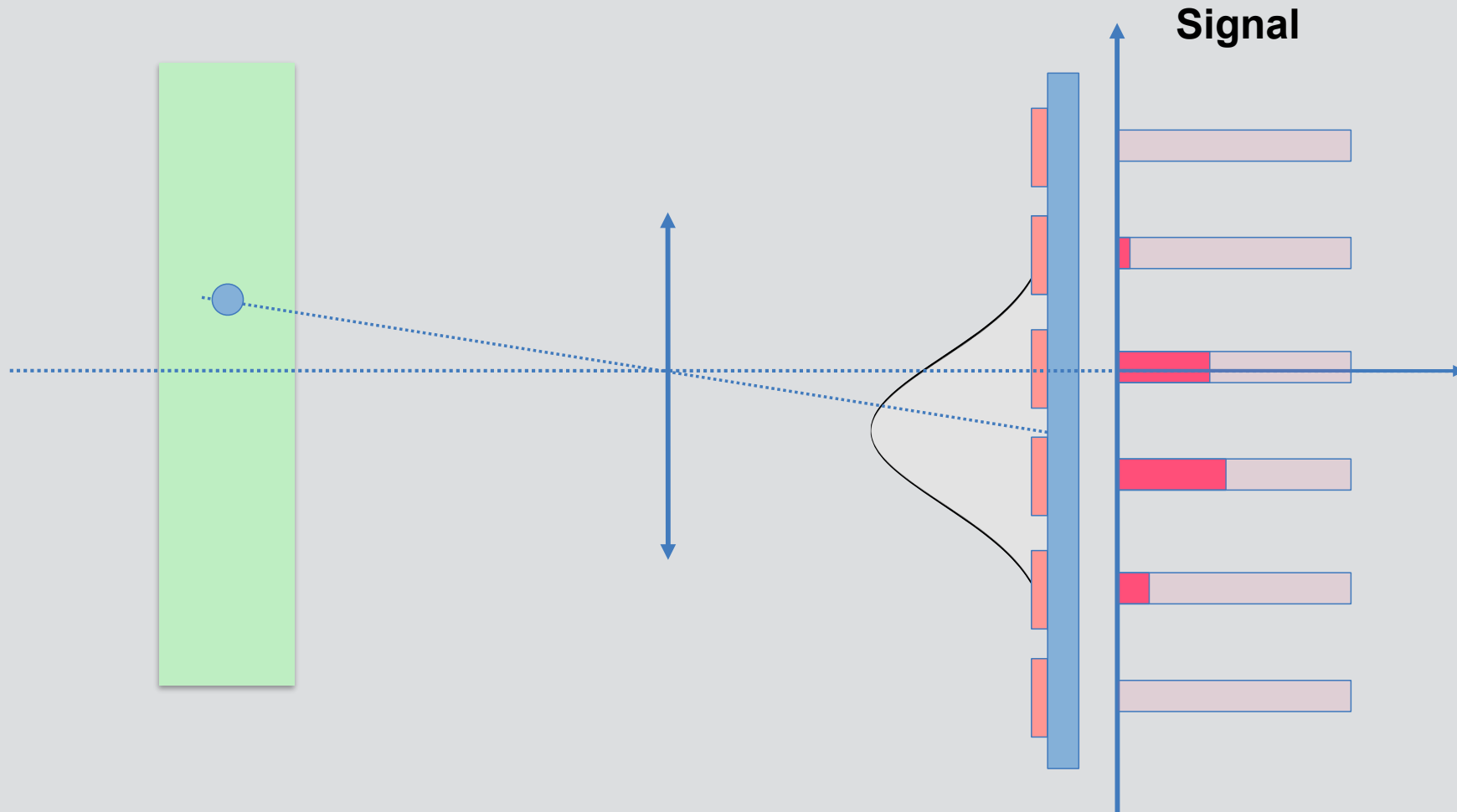
Enregistrement du déplacement d'une particule sur le capteur



Enregistrement du déplacement d'une particule

Principe du sub-pixel 2/4

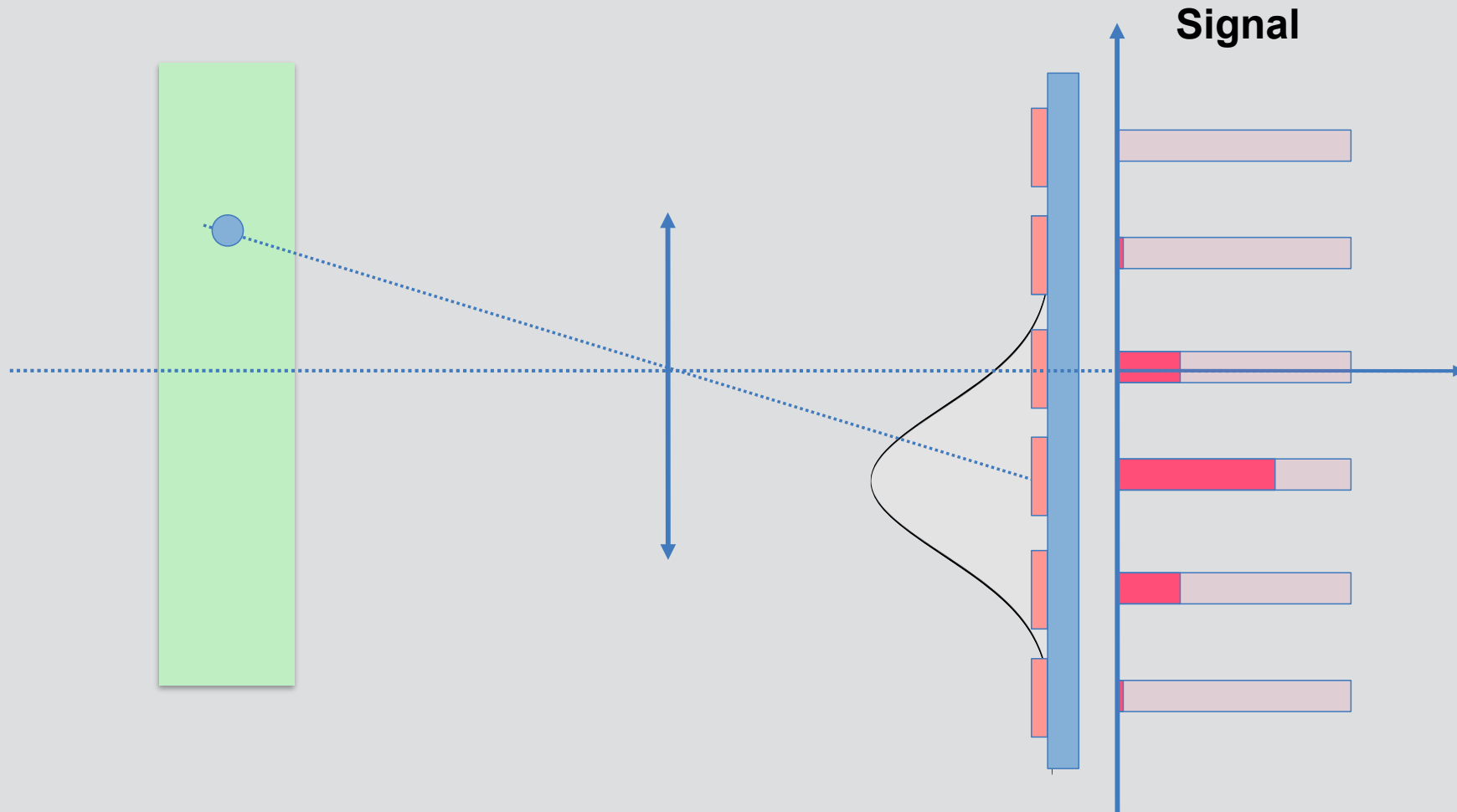
Enregistrement du déplacement d'une particule sur le capteur



Enregistrement du déplacement d'une particule

Principe du sub-pixel 2/4

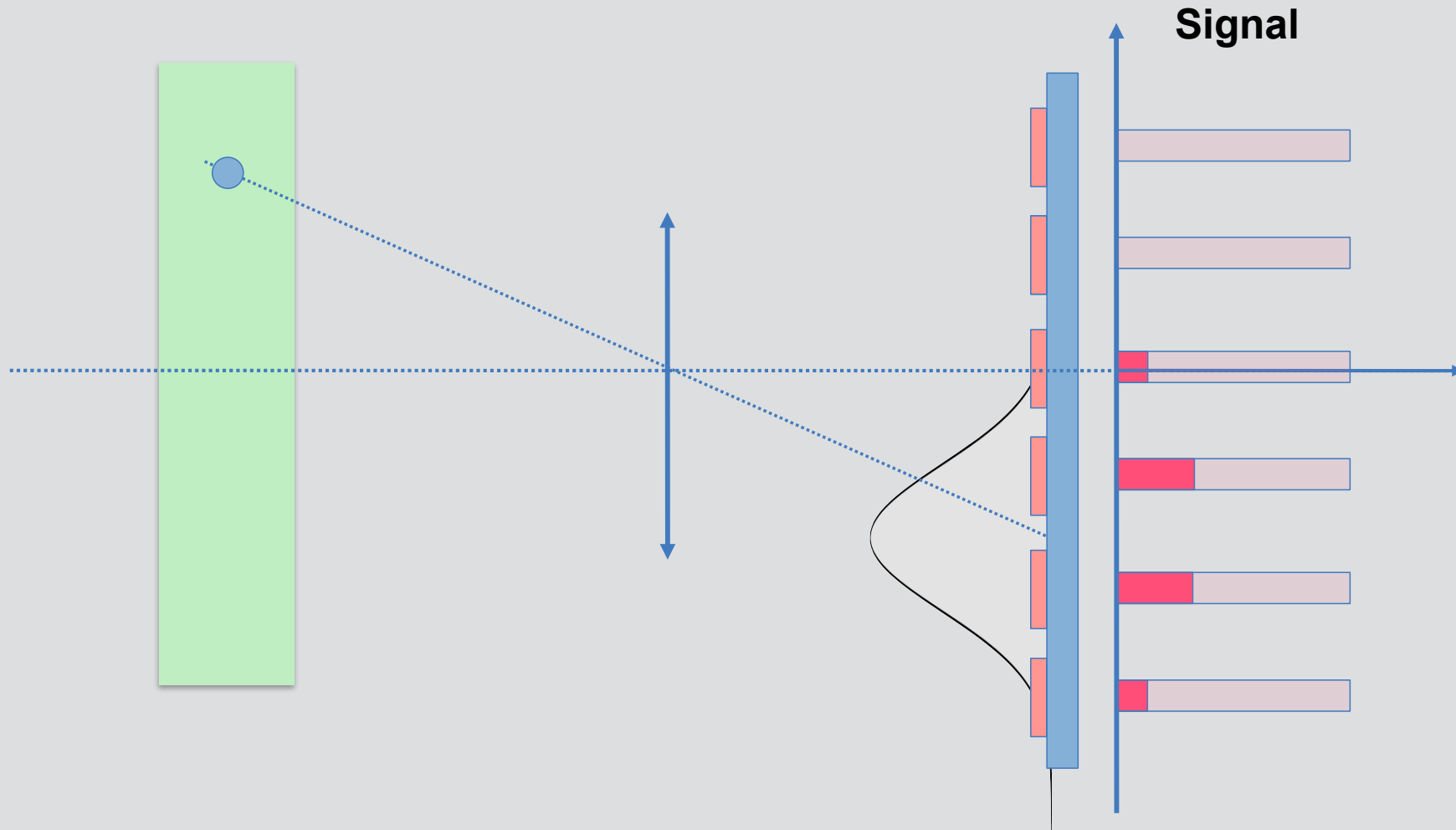
Enregistrement du déplacement d'une particule sur le capteur



Enregistrement du déplacement d'une particule

Principe du sub-pixel 2/4

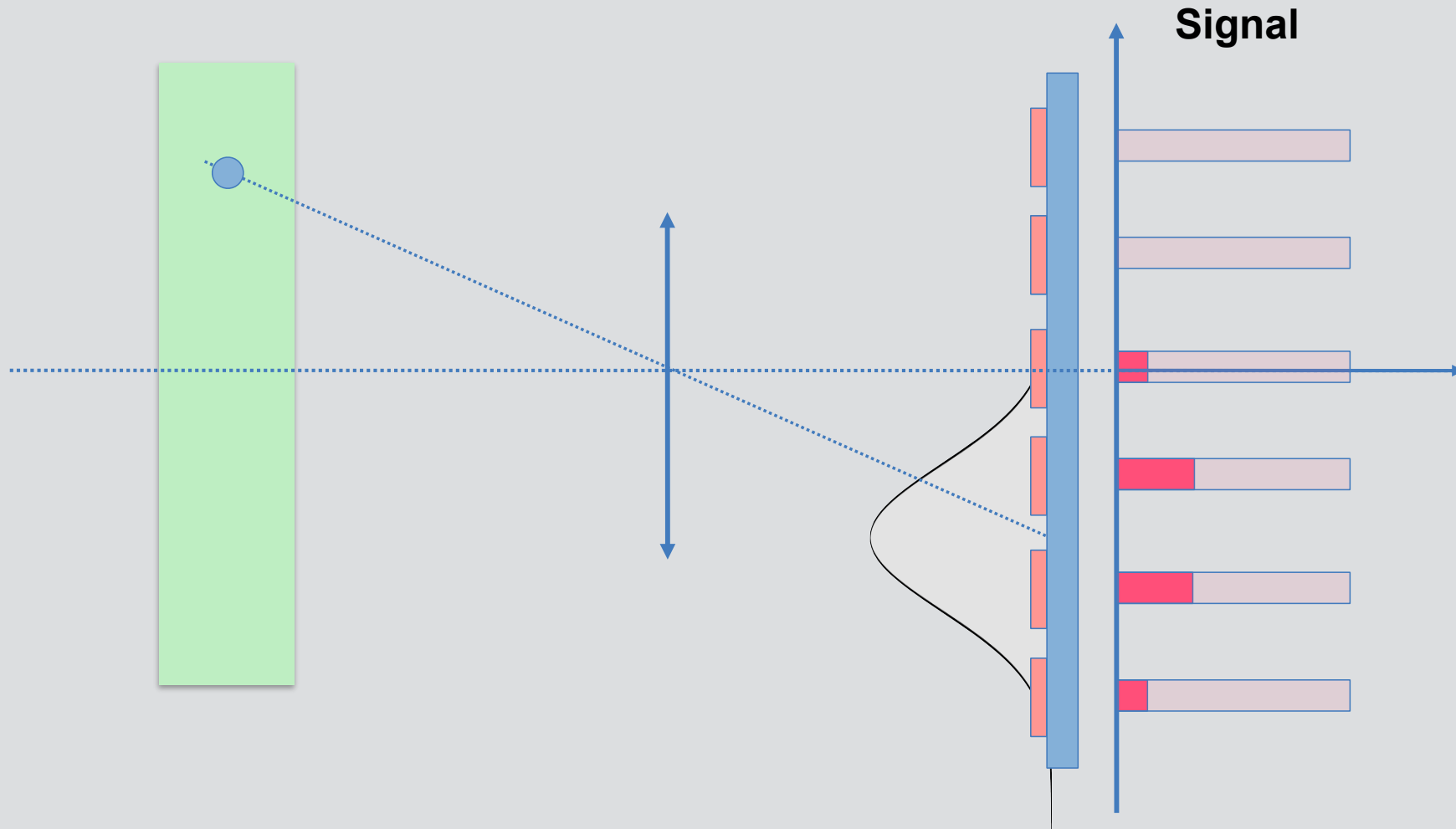
Enregistrement du déplacement d'une particule sur le capteur



Enregistrement du déplacement d'une particule

Principe du sub-pixel 2/4

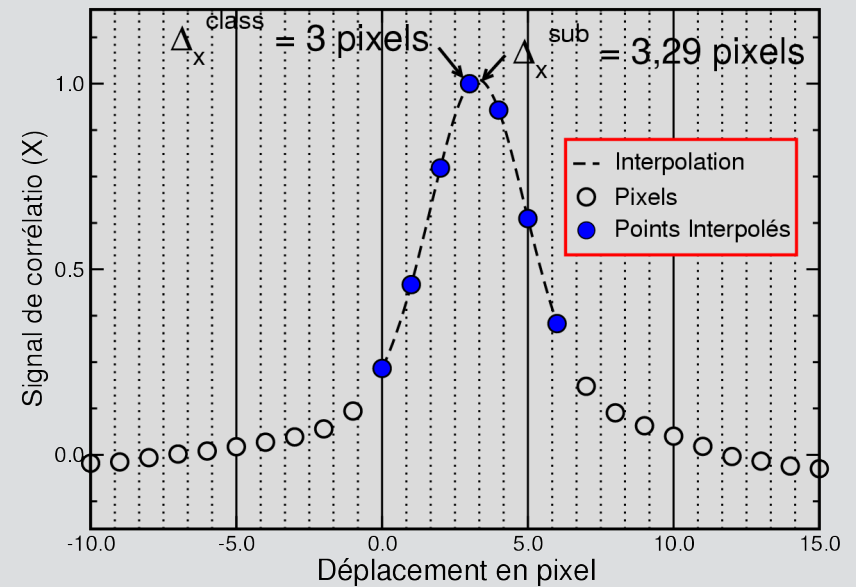
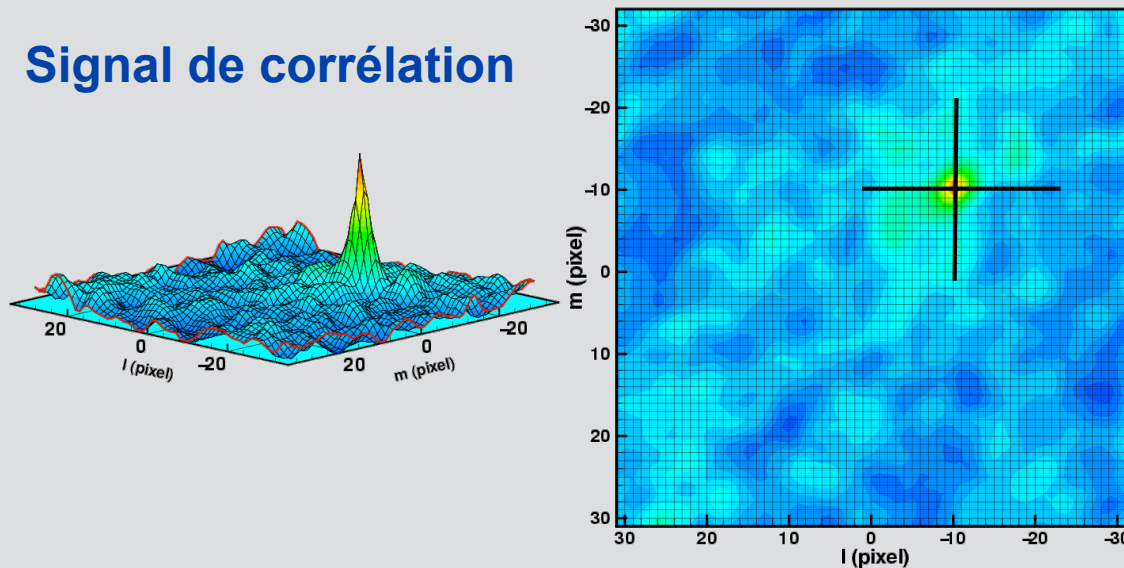
Enregistrement du déplacement d'une particule sur le capteur



Codage du déplacement dans l'enveloppe du signal de l'image de la particule sur le CCD

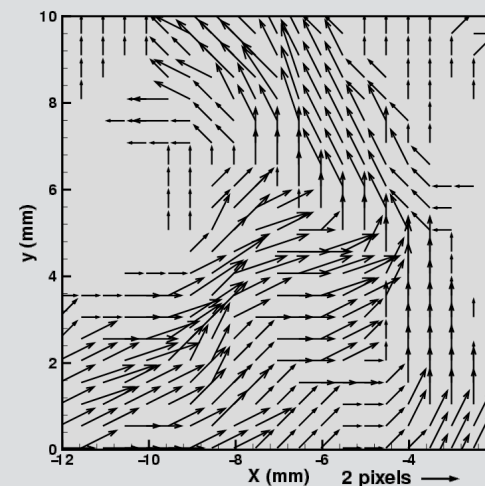
Principe du sub-pixel 3/4

Signal de corrélation

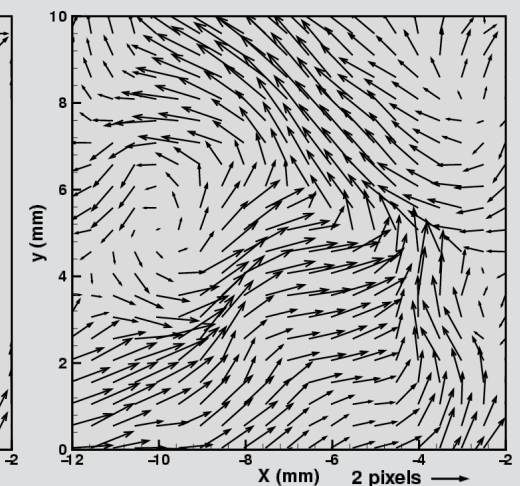


- Différentes méthodes de détection sub-pixel
 - Interpolation gaussienne 2*1D ou 2D
 - Moyenne pondérée, sur-échantillonnage
 - Interpolation Parabolique
- Détection faite sur un nombre impair de point
 - (3x3, 5x5, 7x7...)

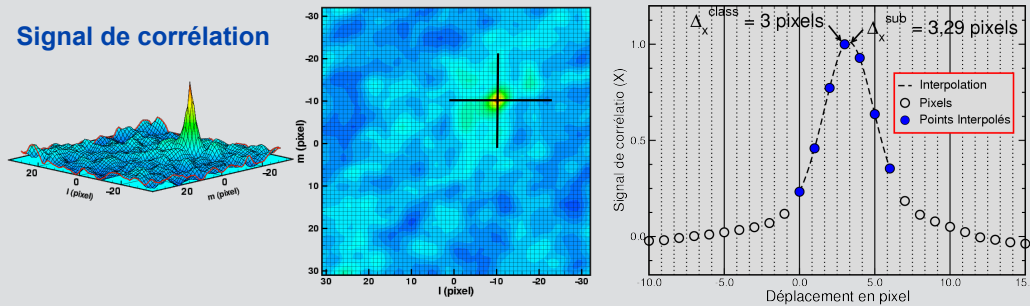
Sans « sub-pixel »



Avec « sub-pixel »



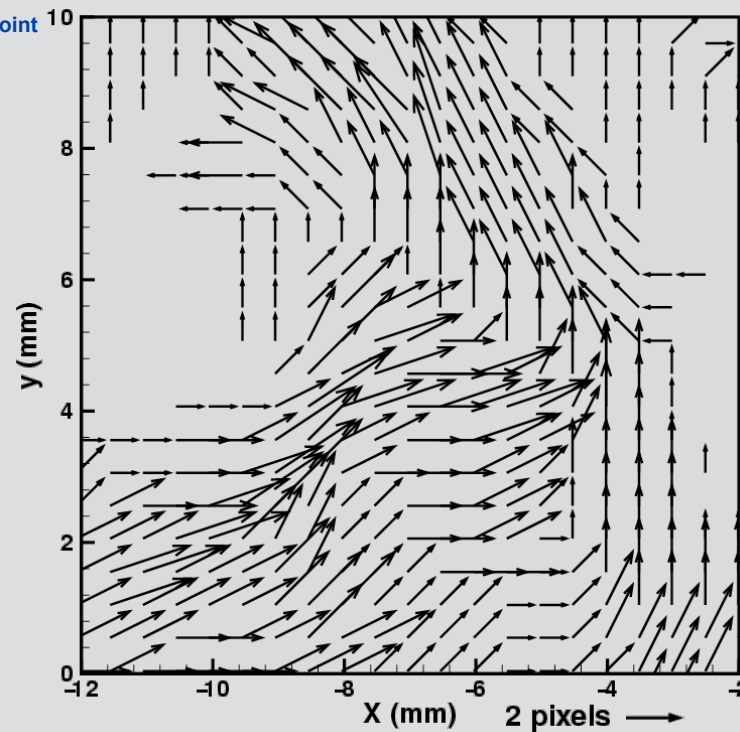
Principe du sub-pixel 3/4



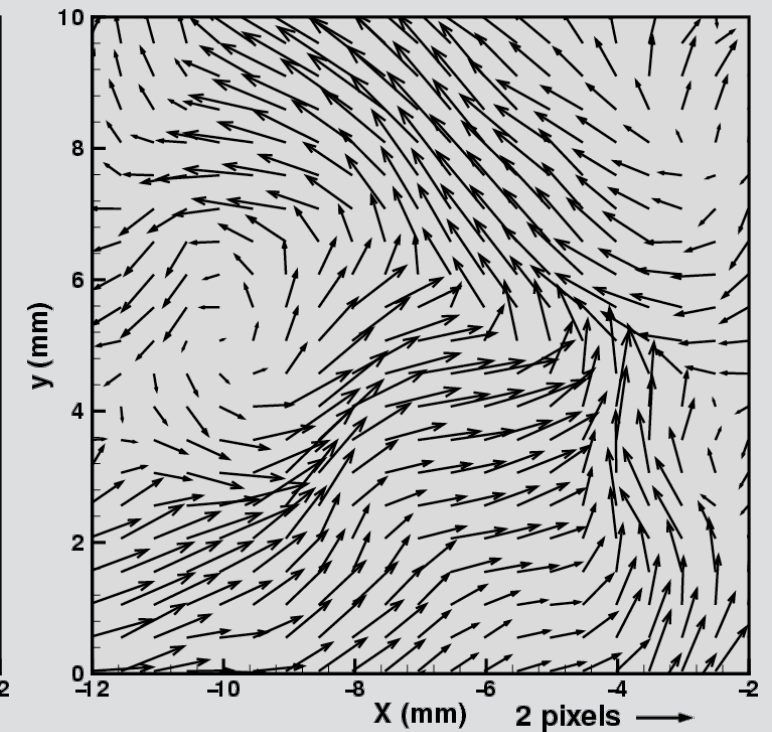
Différentes méthodes de détection sub-pixel

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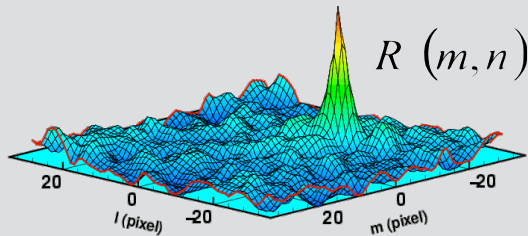
Sans « sub-pixel »



Avec « sub-pixel »



Principe du sub-pixel 4/4 : Principales méthodes d'interpolation



1D Centroid

$$x_0 = \frac{(i-1)R_{(i-1,j)} + iR_{(i,j)} + (i+1)R_{(i+1,j)}}{R_{(i-1,j)} + R_{(i,j)} + R_{(i+1,j)}}$$

$$y_0 = \frac{(j-1)R_{(i,j-1)} + jR_{(i,j)} + (j+1)R_{(i,j+1)}}{R_{(i,j-1)} + R_{(i,j)} + R_{(i,j+1)}}$$

1D Parabolic

$$f(x) = A.x^2 + B.x + C$$

$$x_0 = i + \frac{R_{(i-1,j)} - R_{(i+1,j)}}{2R_{(i-1,j)} - 4R_{(i,j)} + 2R_{(i+1,j)}}$$

$$y_0 = j + \frac{R_{(i,j-1)} - R_{(i,j+1)}}{2R_{(i,j-1)} - 4R_{(i,j)} + 2R_{(i,j+1)}}$$

1D Gaussian

$$f(x) = C \exp \left[\frac{-(x_0 - x)^2}{k} \right]$$

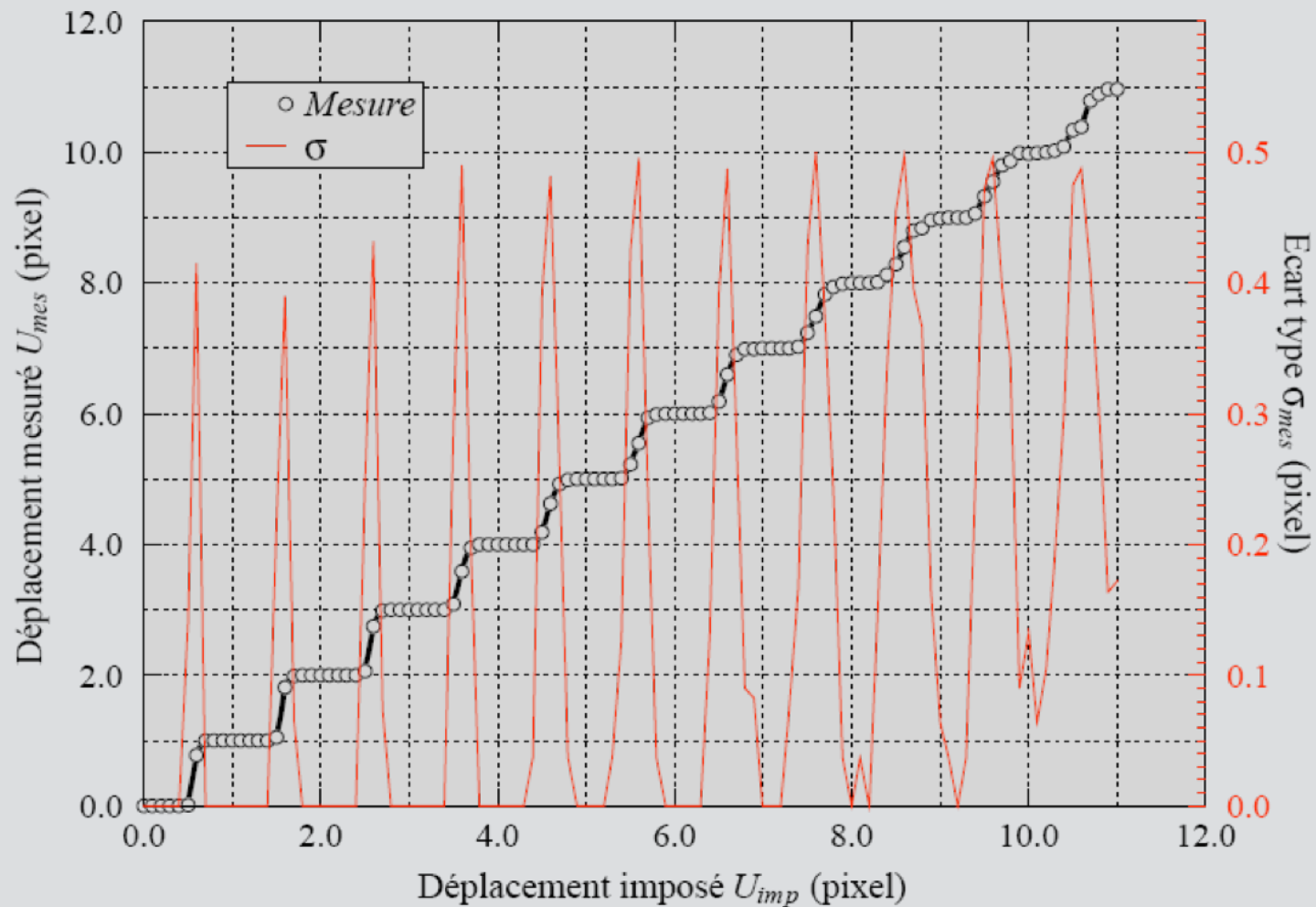
$$x_0 = i + \frac{\ln R_{(i-1,j)} - \ln R_{(i+1,j)}}{2 \ln R_{(i-1,j)} - 4 \ln R_{(i,j)} + 2 \ln R_{(i+1,j)}}$$

$$y_0 = j + \frac{\ln R_{(i,j-1)} - \ln R_{(i,j+1)}}{2 \ln R_{(i,j-1)} - 4 \ln R_{(i,j)} + 2 \ln R_{(i,j+1)}}$$

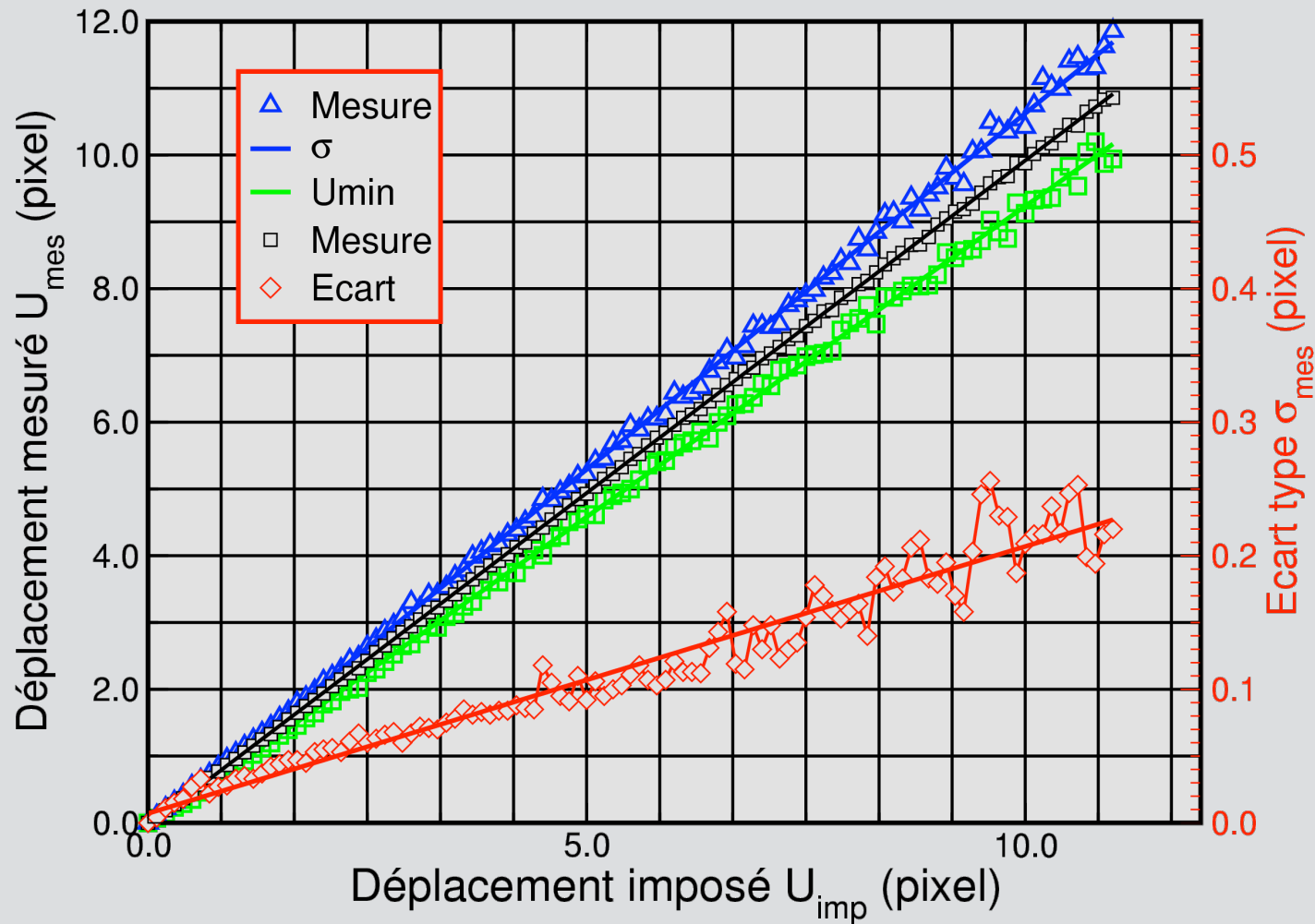
2D extension

To take into account the aspect ratio and the skew of the correlation peak

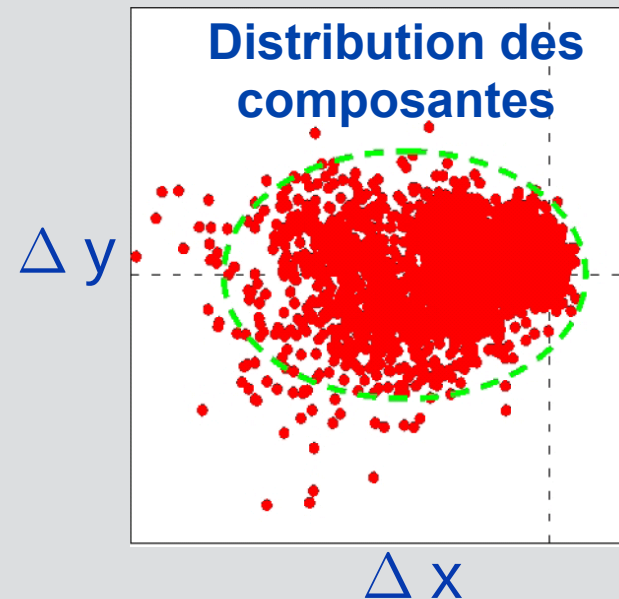
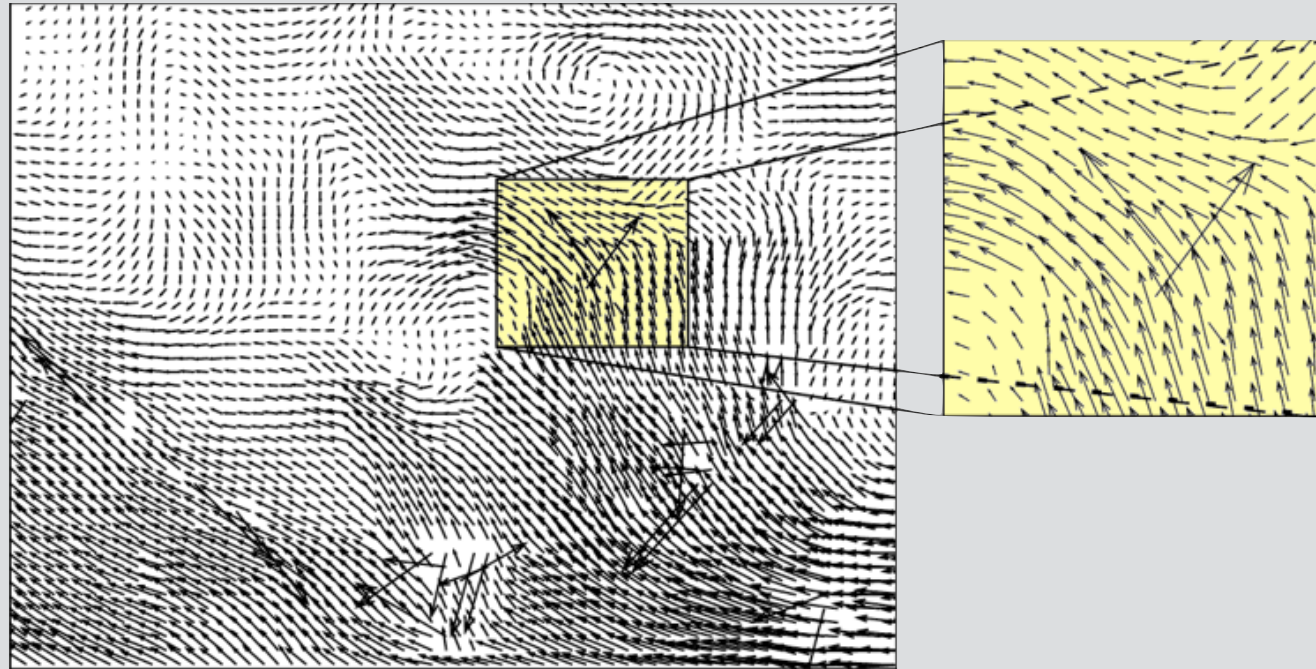
Réponse de la PIV à une vitesse uniforme



Réponse de la PIV à une vitesse uniforme

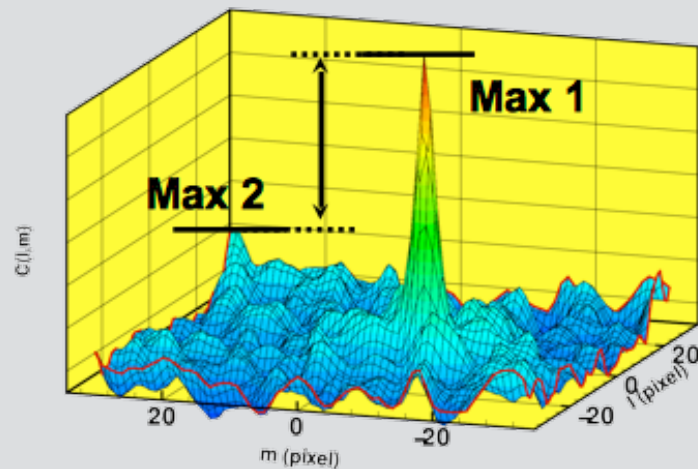


Validation des champs de vitesse 1/2

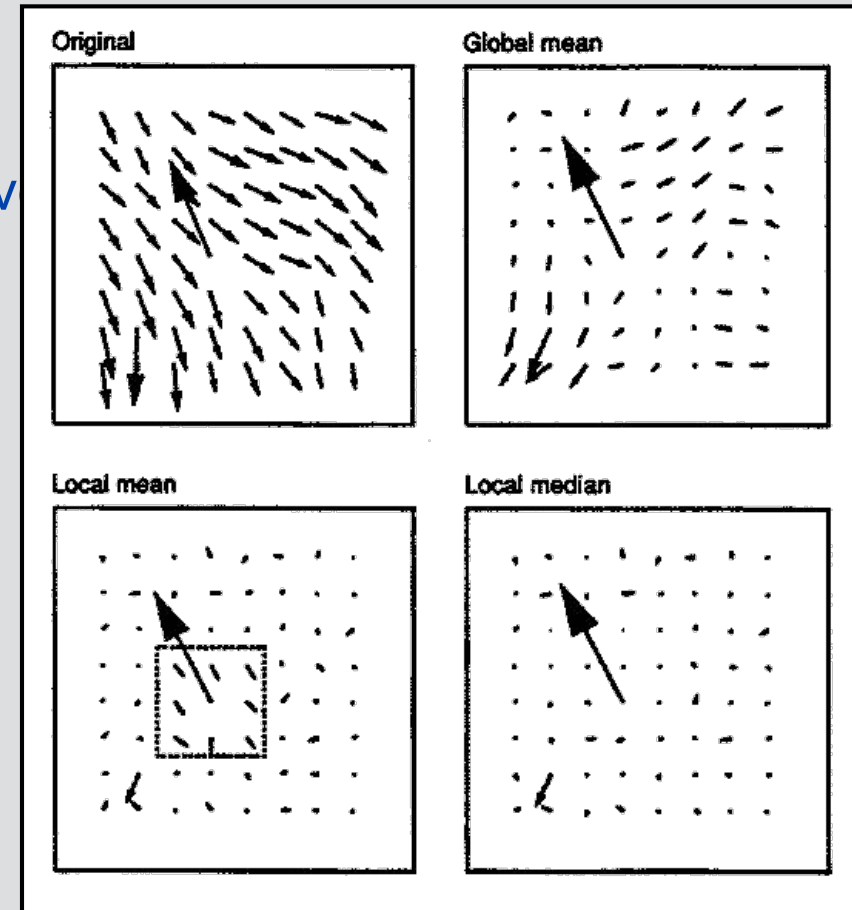


Validation des champs de vitesse 2/2

- Validation par rapport signal sur bruit (ex corrélation)
- Niveau de corrélation
- Validation par longueur maximum
- Validation par comparaison avec les v



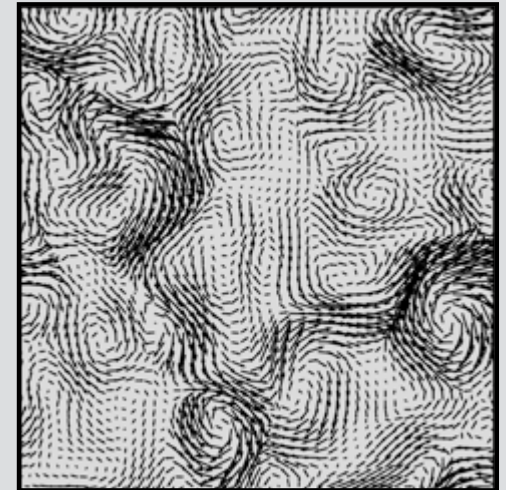
$$\text{RSB} = \text{Max2/Max1}$$



Attention : Interpolation ou non des vecteurs non validés

Résumé de la procédure complète

- Ensemencement de l'écoulement
- Illumination d'une tranche à l'aide d'un laser ou LED
- Enregistrement de 2 images successives (ou plus)
- Analyse des images de particules
 - Approche particulière (PTV)
 - Approche statistique (Corrélation)
- Validation des champs de vitesse
- Exploitation des champs de vitesse
 - Moyenne, fluctuation, détection structure



Les sources d'erreur

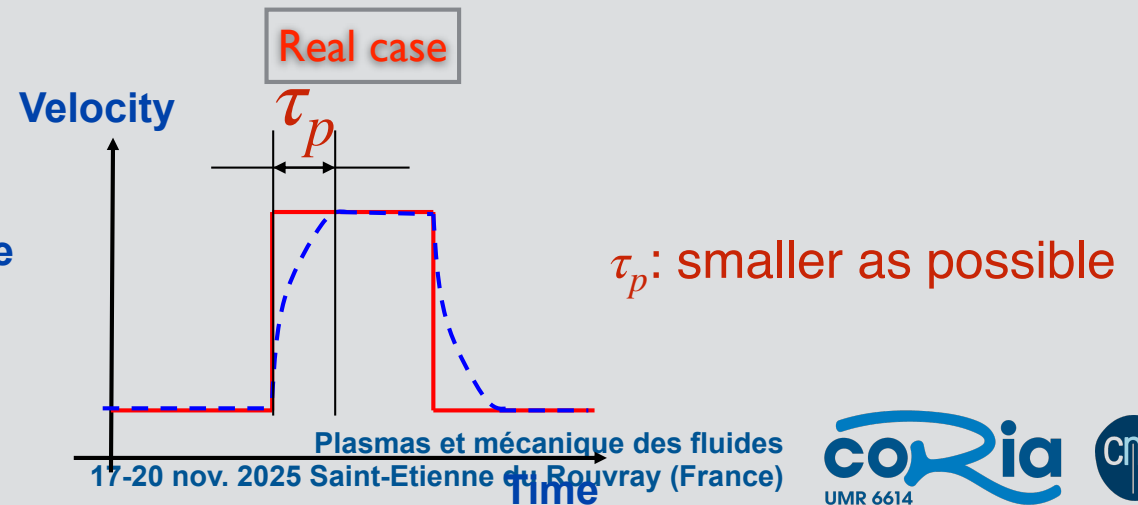
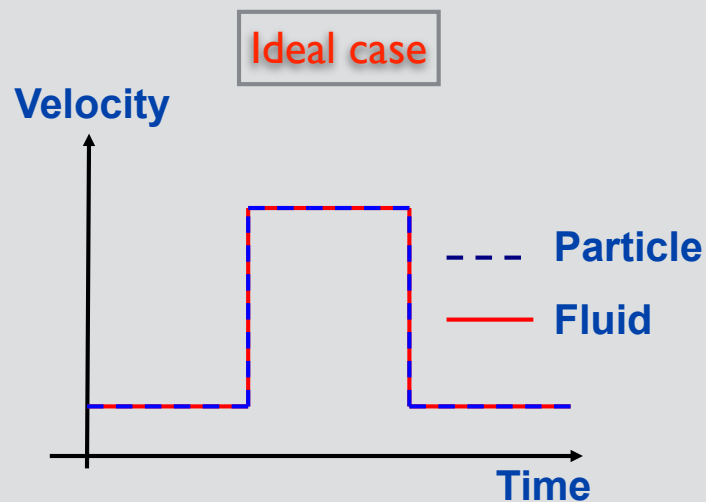
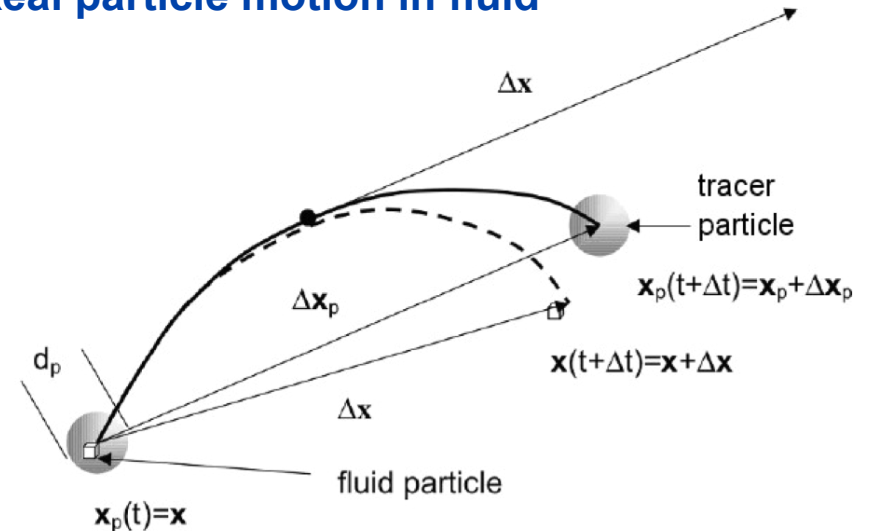
Seeding: Particle velocity lag

PIV: Substitute the measurement of fluid velocity by the velocity of particles transported by fluid

→ Are the particles follow the flow ? $\vec{V}_{fluid} \stackrel{?}{=} \vec{V}_p$



Real particle motion in fluid



Seeding: Particle velocity lag

Motion of a small spherical particle in unsteady flow at low Reynolds numbers

Basset–Boussinesq–Oseen equation

$$\underbrace{\frac{\pi}{6} \rho_p d_p^3 \frac{du_p}{dt}}_{T_1} = \underbrace{-3\pi\mu d_p (u_p - u_f)}_{T_2} + \underbrace{\frac{\pi d_p^3}{6} \rho_f \frac{du_f}{dt}}_{T_3} - \underbrace{\frac{1}{2} \frac{\pi d_p^3}{6} \rho_f \frac{d(u_p - u_f)}{dt}}_{T_4} - \underbrace{\frac{3}{2} d_p^2 \sqrt{\pi\mu\rho_f} \int_{t_0}^t \frac{d(u_p - u_f)}{d\xi} \frac{d\xi}{\sqrt{t - \xi}}}_{T_5} + F_{ext}$$

T_1 : Accelerating force

T_2 : Strokes drag force

T_3 : Pressure gradient force on fluid

T_4 : Fluid resistance to accelerating sphere

T_5 : Drag force associated with unsteady motion (Basset's force)

F_{ext} : Other external forces (gravity, thermophoresis, magnetic...)

u_p : Particle velocity

d_p : Particle diameter

ρ_p : Particle density

u_f : Fluid velocity

ρ_f : Fluid density

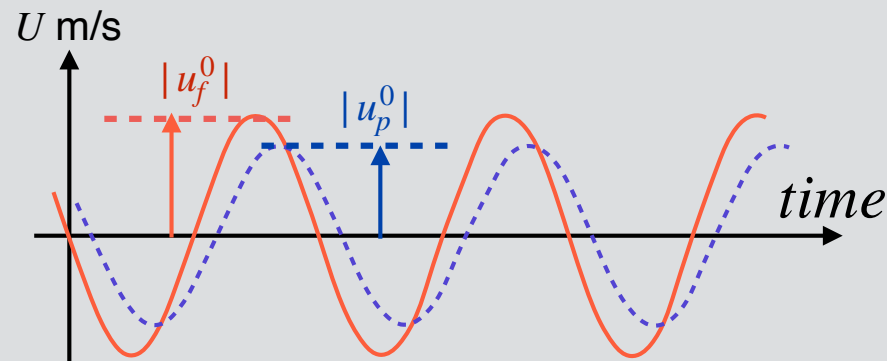
μ : Fluid viscosity

In air: $\rho_f \ll \rho_p$

$$\frac{du_p}{dt} \approx -\frac{18\mu}{\rho_p d_p^2} (u_p - u_f) = -\frac{1}{\tau_p} (u_p - u_f)$$

Seeding: Particle velocity lag - Particle response time

$$\frac{du_p}{dt} = -\frac{18\mu}{\rho_p d_p^2}(u_p - u_f) = -\frac{1}{\tau_p}(u_p - u_f) \quad \text{with } \tau_p = \frac{\rho_p d_p^2}{18\mu}$$



— Fluid $u_f(t) = u_f^0 e^{i\omega t} = u_f^0 e^{i2\pi f t}$

- - - Particle (solution) $u_p(t) = u_p^0 e^{i\omega t} = u_p^0 e^{i2\pi f t}$

$$\Rightarrow u_p(t) = \frac{1}{1 + i\omega\tau_p} u_f(t) \quad u_p^0 = \frac{u_f^0}{1 + i\omega\tau_p} \Rightarrow \left(|u_p^0| \leq |u_f^0| \right)$$

Phase shift

$$\left| \frac{u_p^0}{u_f^0} \right|^2 = \frac{1}{1 + (\omega\tau_p)^2} = \frac{1}{1 + (2\pi f\tau_p)^2}$$

For -3 dB attenuation: $\Rightarrow$

cutoff-frequency

$$f_c(-3dB) = \frac{1}{2\pi\tau_p}$$

Seeding: Particle velocity lag - Particle response time

$$\frac{du_p}{dt} = -\frac{18\mu}{\rho_p d_p^2}(u_p - u_f) = -\frac{1}{\tau_p}(u_p - u_f) \quad \text{with } \tau_p = \frac{\rho_p d_p^2}{18\mu}$$



Particles*	n_p	ρ_p	0.5 μm		1 μm		2 μm	
			$t_1, \mu\text{s}$	$f_{3\text{-dB}}, \text{kHz}$	$t_1, \mu\text{s}$	$f_{3\text{-dB}}, \text{kHz}$	$t_1, \mu\text{s}$	$f_{3\text{-dB}}, \text{kHz}$
Silicon carbide	2.6	3.3	2.55	62	10.2	16	41	3.9
Alumina	1.76	3.8	2.93	54	11.7	14	47	3.0
Polystyrene	1.6	1.05	0.81	196	3.24	52	13	13
Peanut oil	1.47	0.91	0.70	227	2.81	57	11.2	14
Microballoons		0.23	0.18	897	0.71	224	2.84	56

* For air, settling velocity = $9.8t_1$ (m/s).

Seeding: Particle velocity lag - Thermophoretic force

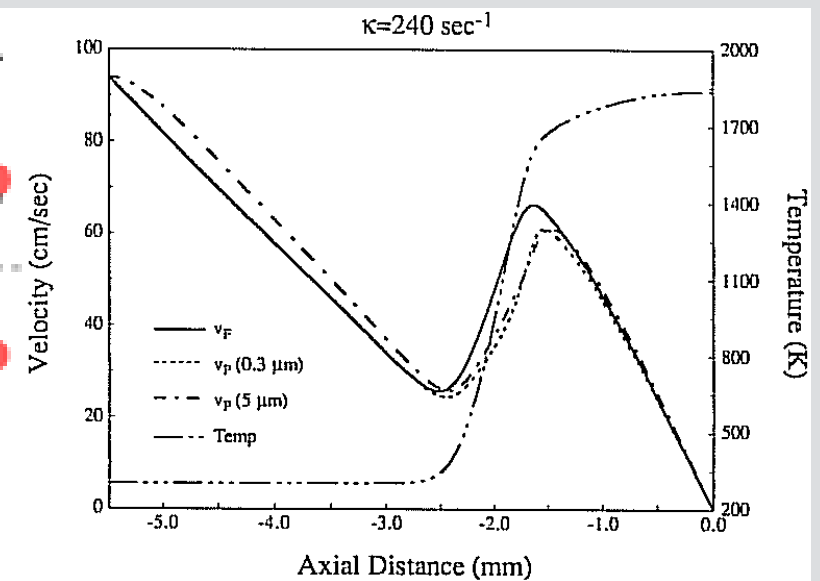
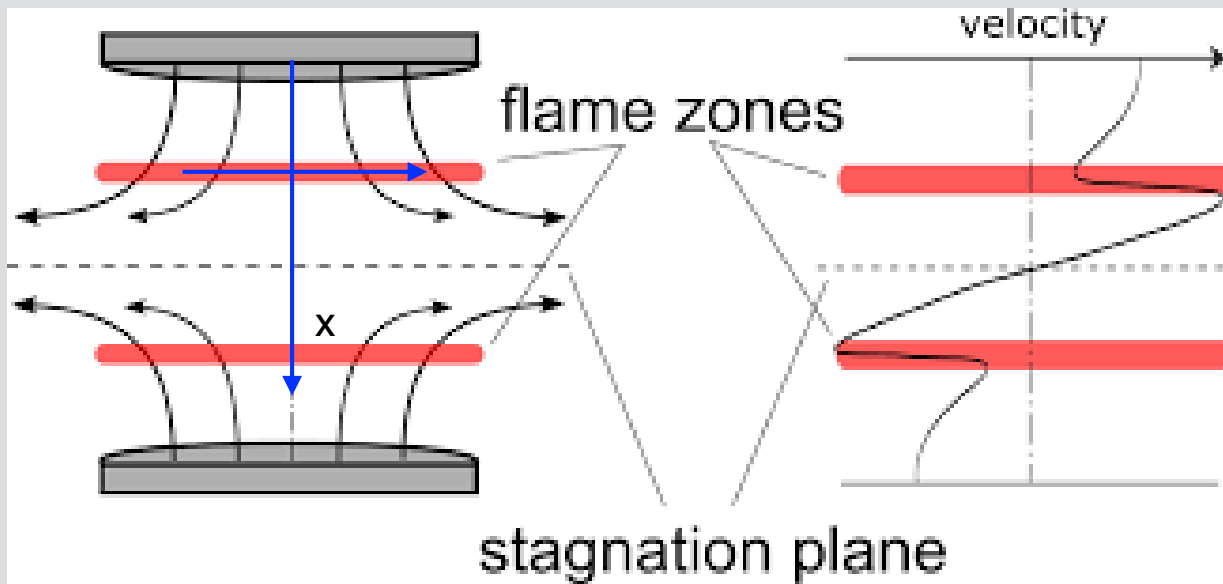
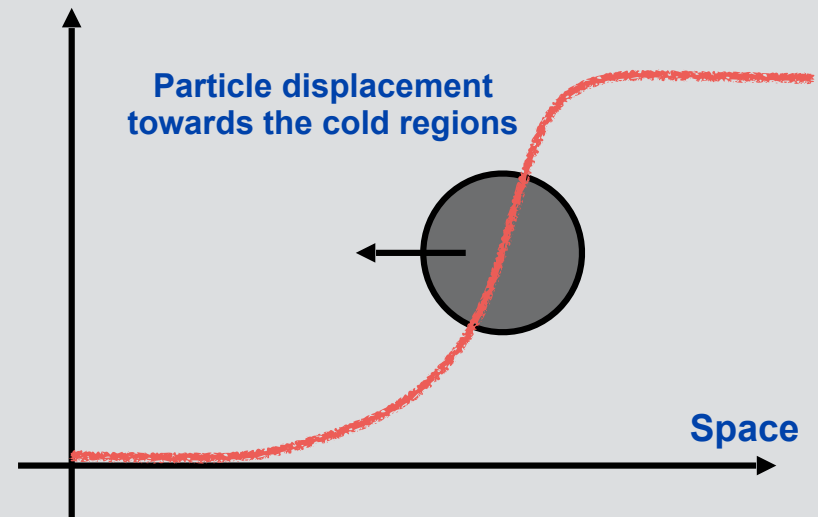
Particle size of same order of magnitude
that the temperature gradient
(Flame, thermal boundary layer...)

Thermophoretic force

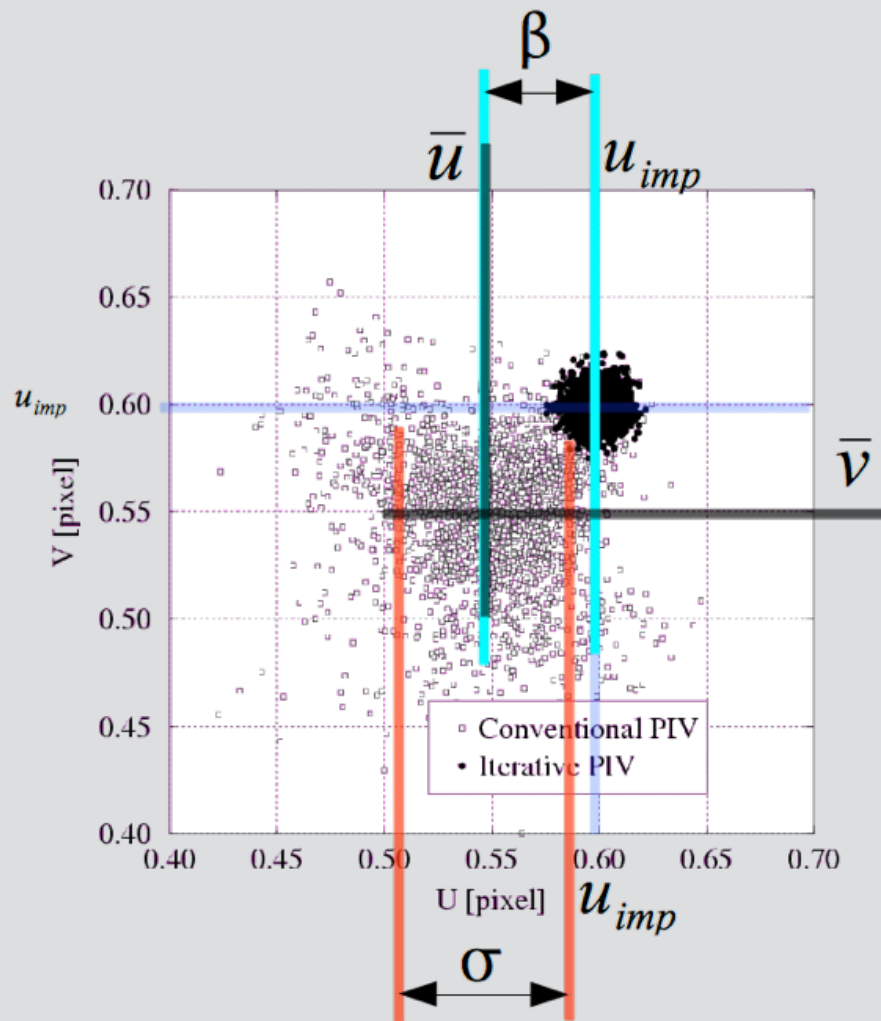
$$F_{tp} \propto d_p \frac{\nabla T}{T}$$

Temperature

Particle displacement
towards the cold regions



Définition des erreurs



Bias Error

$$\beta = u_{imp} - \frac{1}{N} \sum_{i=1}^N u_i = u_{imp} - \bar{u}$$

Constant systematic portion of measurement error

Random Error

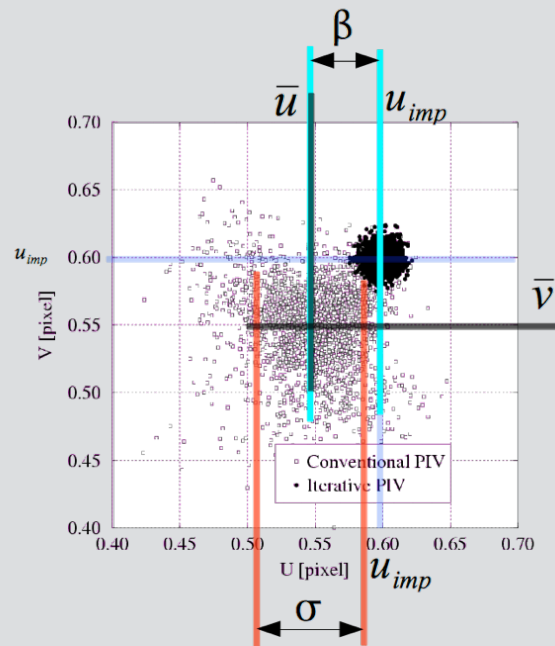
$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (u_i - \bar{u})^2}$$

Random portion of measurement error

Total Error

$$\delta = \sqrt{\frac{1}{N} \sum_{i=1}^N (u_i - u_{imp})^2} = \sqrt{\beta^2 + \sigma^2}$$

Définition des erreurs



Bias Error

$$\beta = u_{imp} - \frac{1}{N} \sum_{i=1}^N u_i = u_{imp} - \bar{u}$$

Constant systematic portion of measurement error

Random Error

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (u_i - \bar{u})^2}$$

Random portion of measurement error

Total Error

$$\delta = \sqrt{\frac{1}{N} \sum_{i=1}^N (u_i - u_{imp})^2} = \sqrt{\beta^2 + \sigma^2}$$

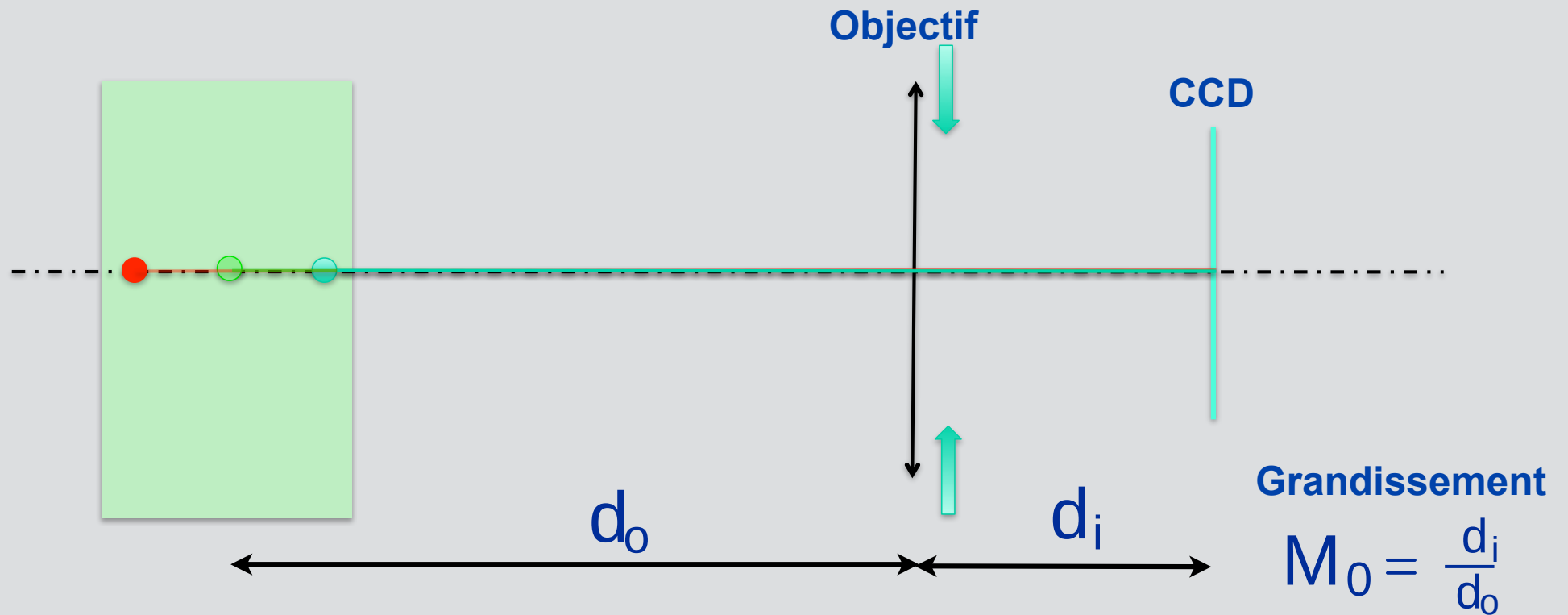
Biais systématiques

- Effet de la perspective
- Déformation optique
- Phénomène de blocage de pic (peak-locking)

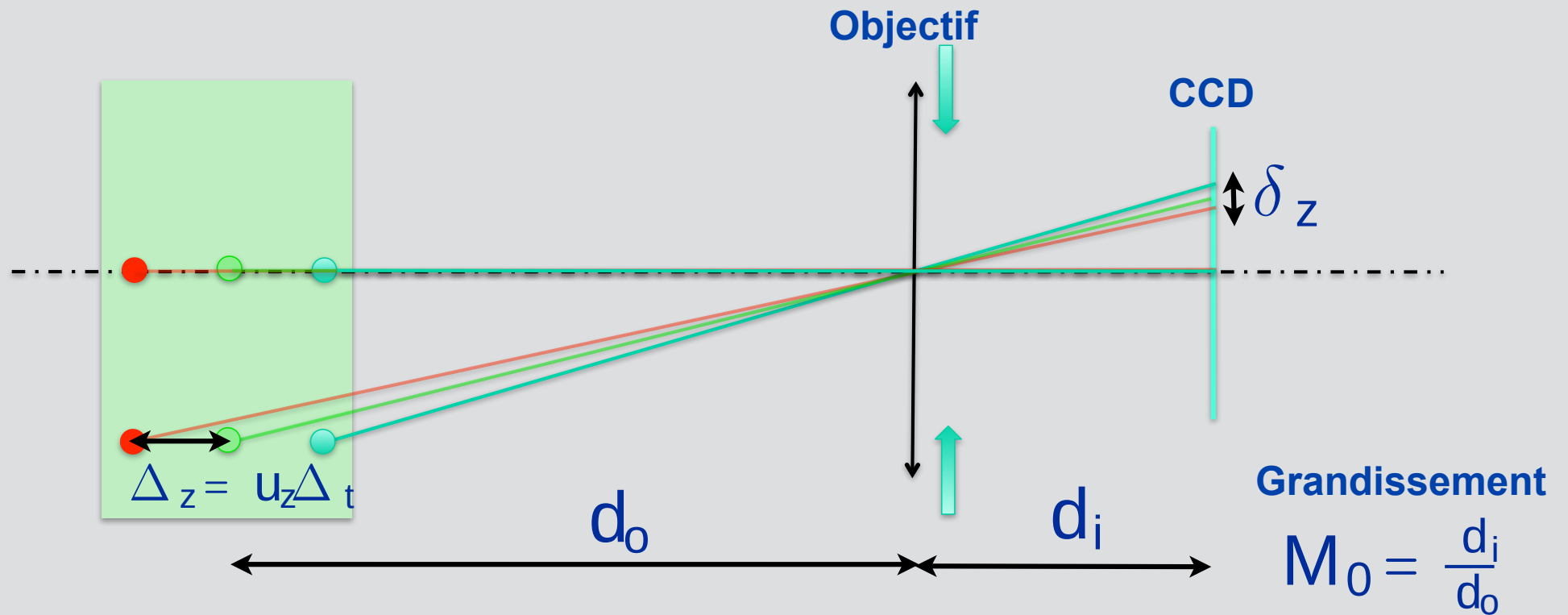
Erreurs aléatoires

- Vitesses dans le plan (in-plane particle motion)
- Vitesses perpendiculaires au plan (out-of-plane particle motion)
- ...

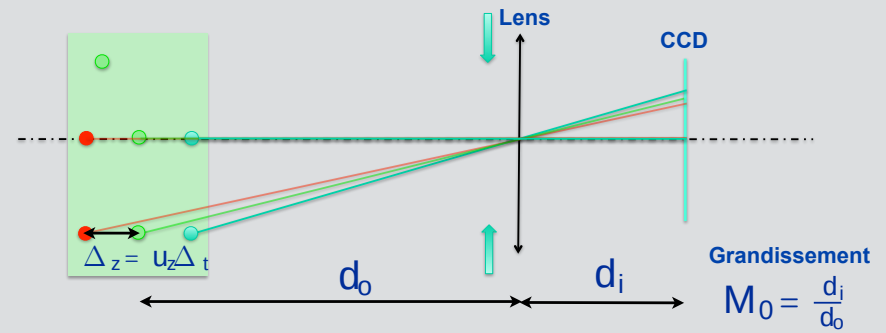
Biais : Effect de perspective 1/2



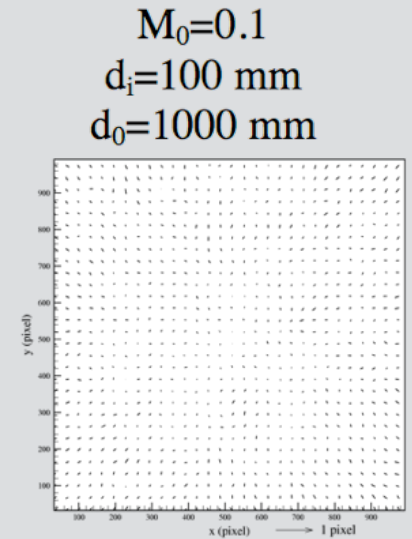
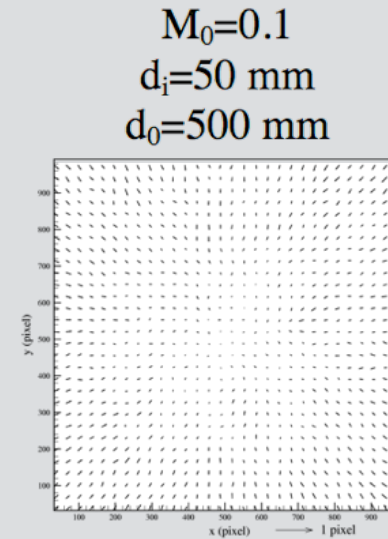
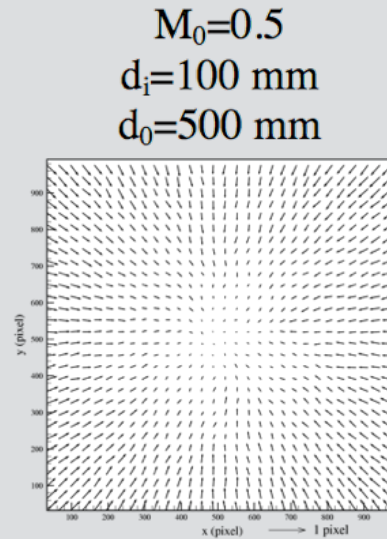
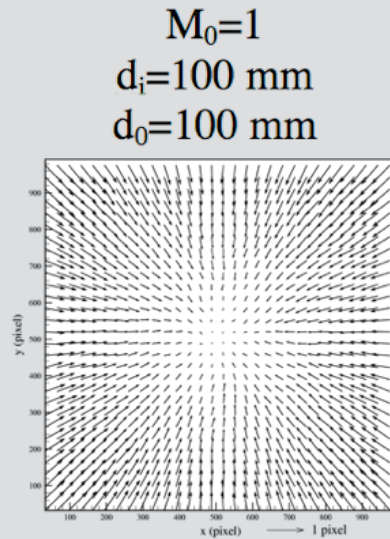
Biais : Effect de perspective 1/2



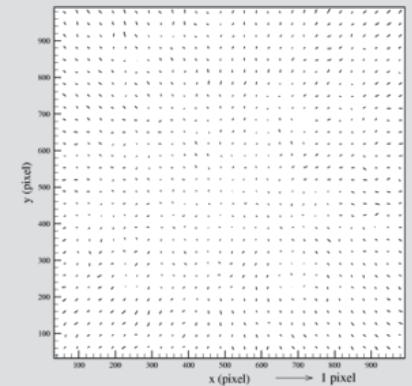
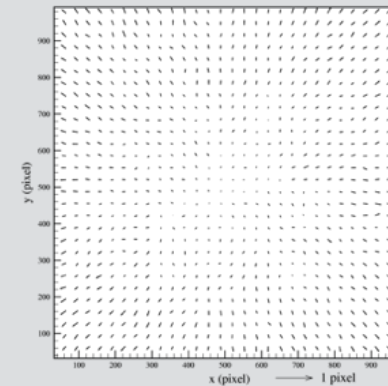
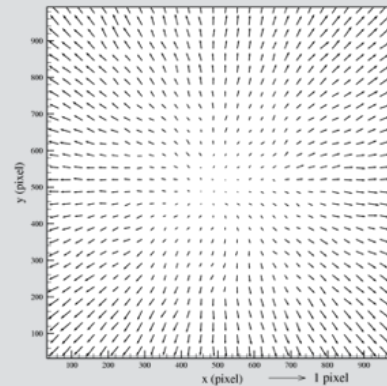
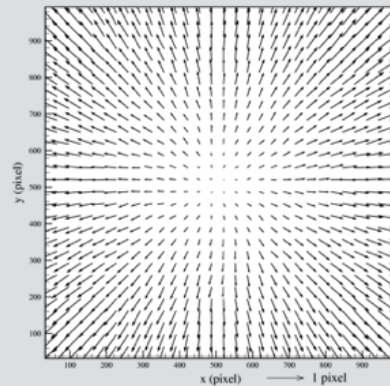
Biais : Effect de perspective 1/2



$$\Delta_z = 1 \text{ } 0 \mu\text{m}$$



$$\Delta_z = -1 \text{ } 0 \mu\text{m}$$



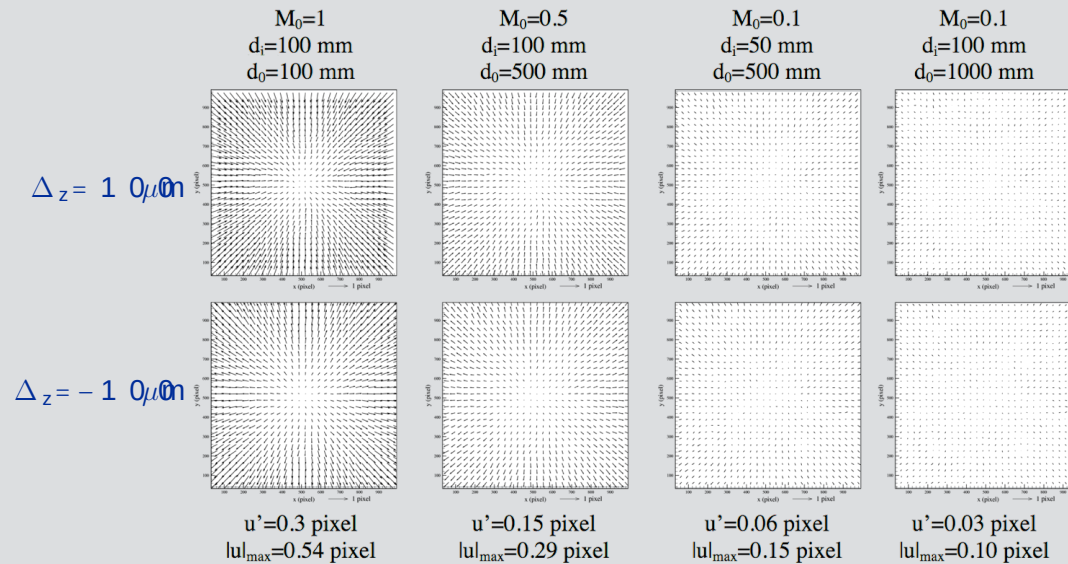
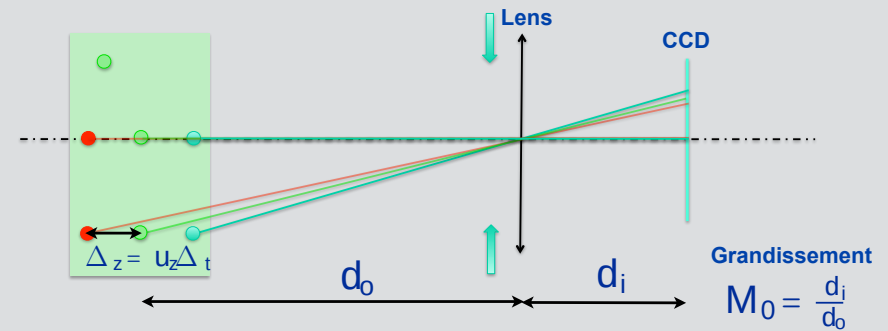
$u'=0.3 \text{ pixel}$
 $|u|_{\max}=0.54 \text{ pixel}$

$u'=0.15 \text{ pixel}$
 $|u|_{\max}=0.29 \text{ pixel}$

$u'=0.06 \text{ pixel}$
 $|u|_{\max}=0.15 \text{ pixel}$

$u'=0.03 \text{ pixel}$
 $|u|_{\max}=0.10 \text{ pixel}$

Biais : Effect de perspective 1/2



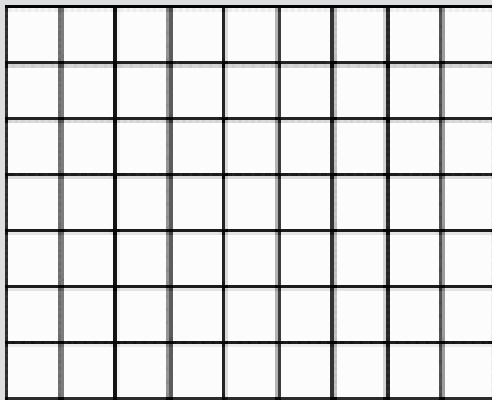
Biais systématique

- Grandissement optique
- Position de la particule en (x,y,z)
- Composante de vitesse u_z
- Epaisseur du plan laser
- Souvent négligeable dès que $M_0 < 0.1$

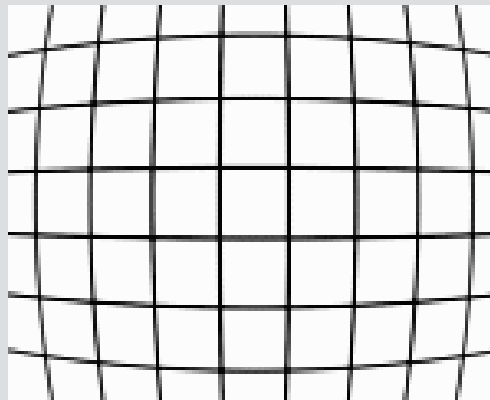
Biais : Déformation optique

Type de déformation $r_u = r_d + k_1 r_d^3$

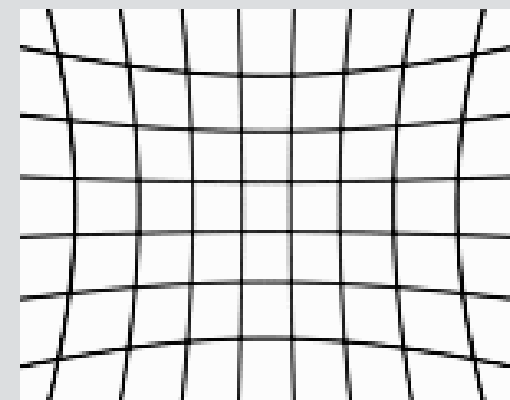
No distortion



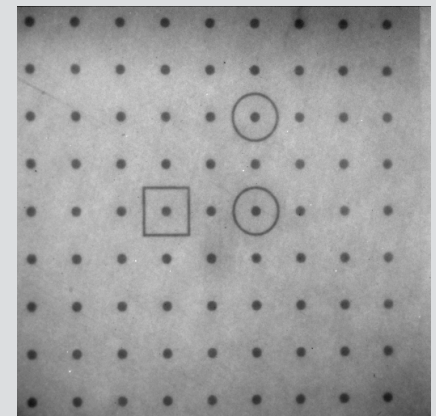
Barrel ($k_1 > 0$)



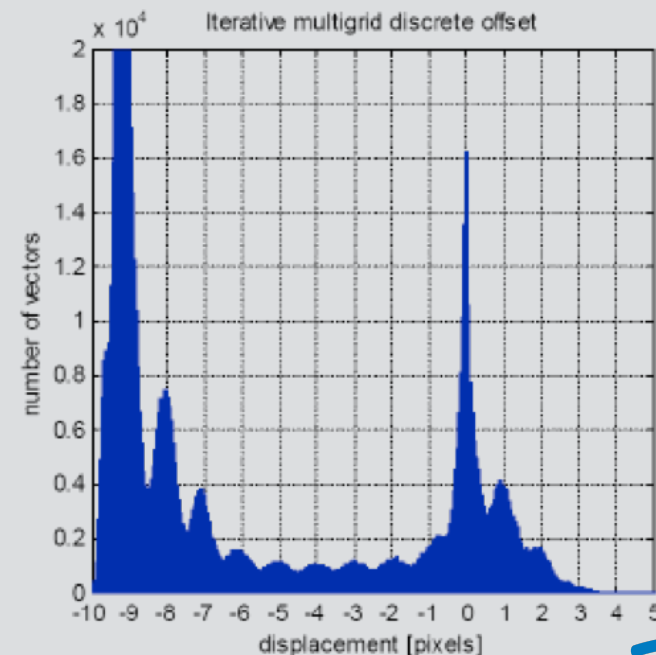
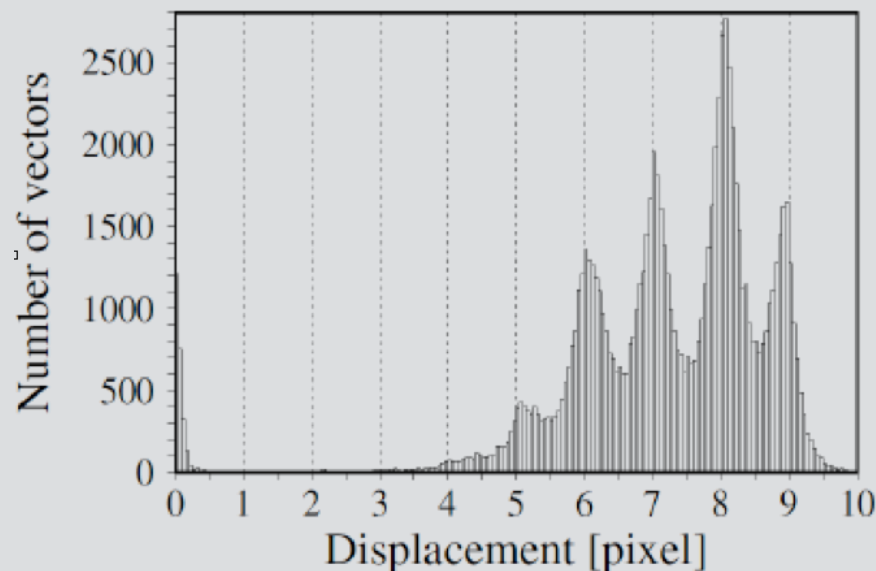
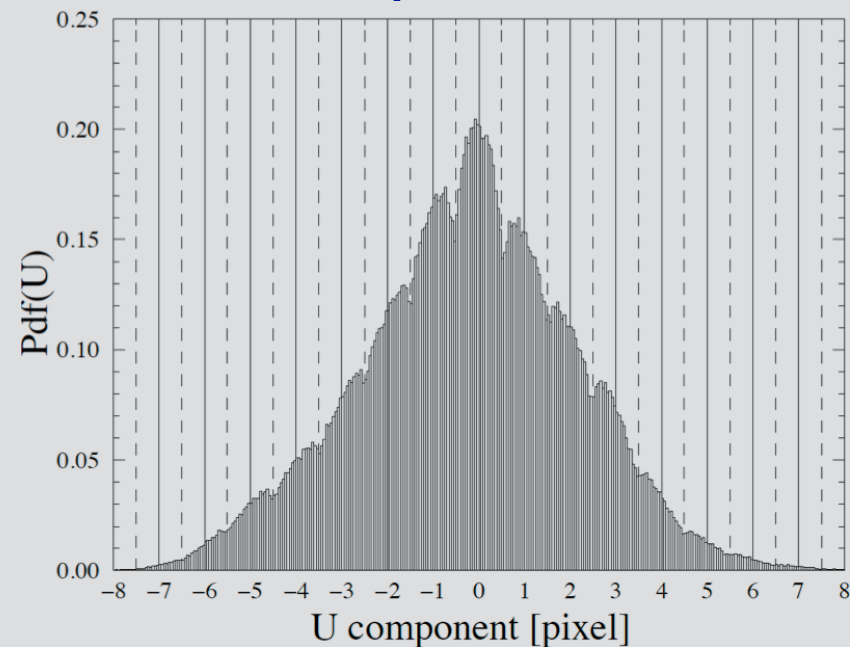
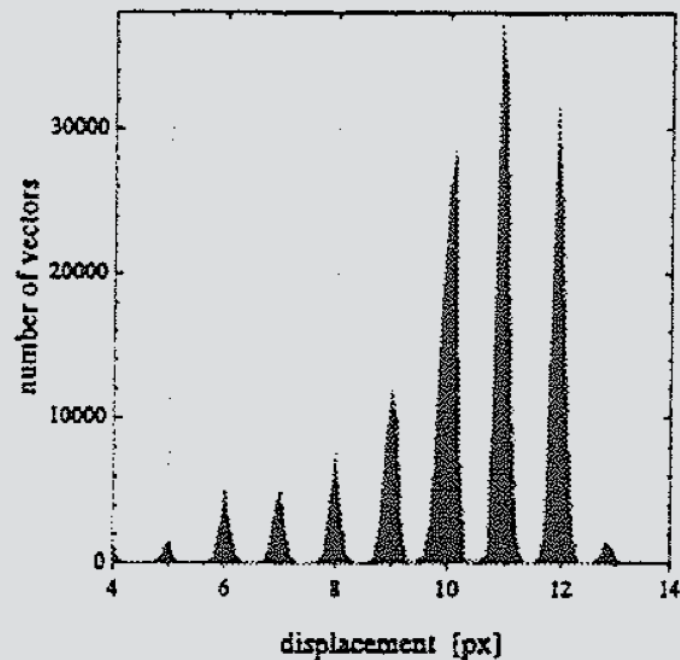
Pincushion ($k_1 < 0$)



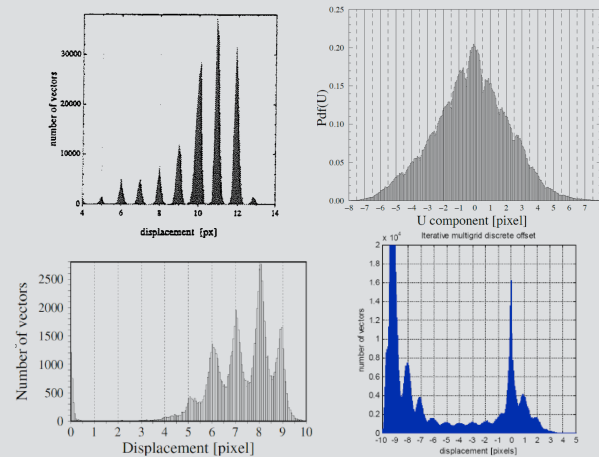
- Grandissement variable en fonction de la position
- Déformation des motifs de particules
- Correction possible à partir d'une calibration spatiale



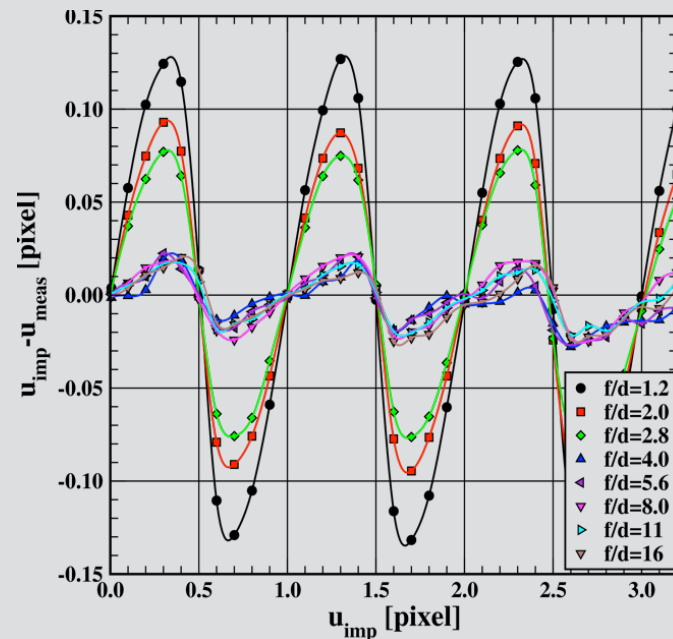
Biais : Exemples de mesures avec du blocage de pic (histogramme de vitesse)



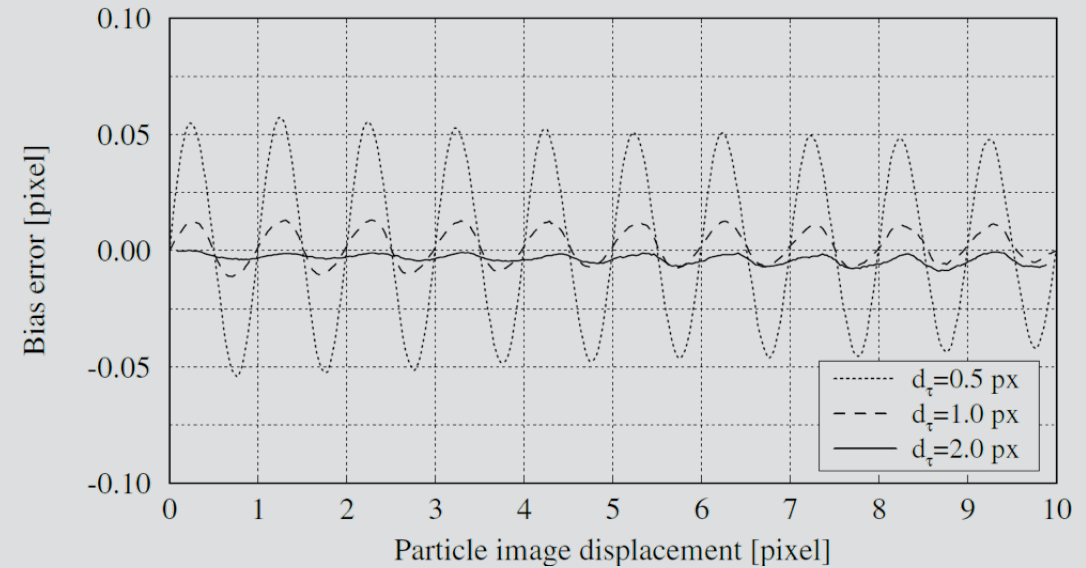
Biais : Evolution de l'erreur de biais en fonction du déplacement



Expérience



Simulation

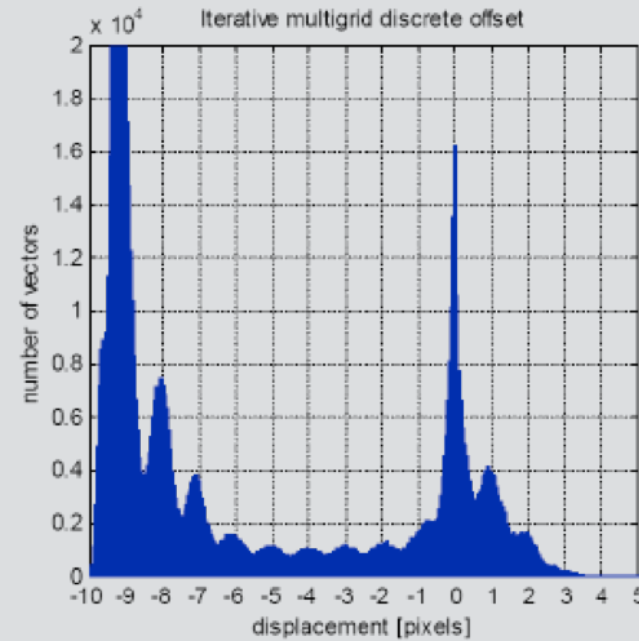
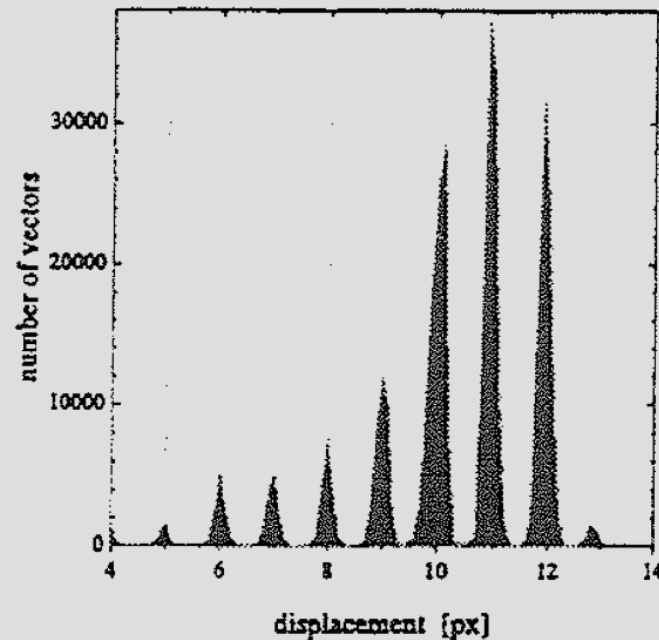


Bias Error

$$\beta = u_{imp} - \frac{1}{N} \sum_{i=1}^N u_i = u_{imp} - \bar{u}$$

Constant systematic portion of measurement error

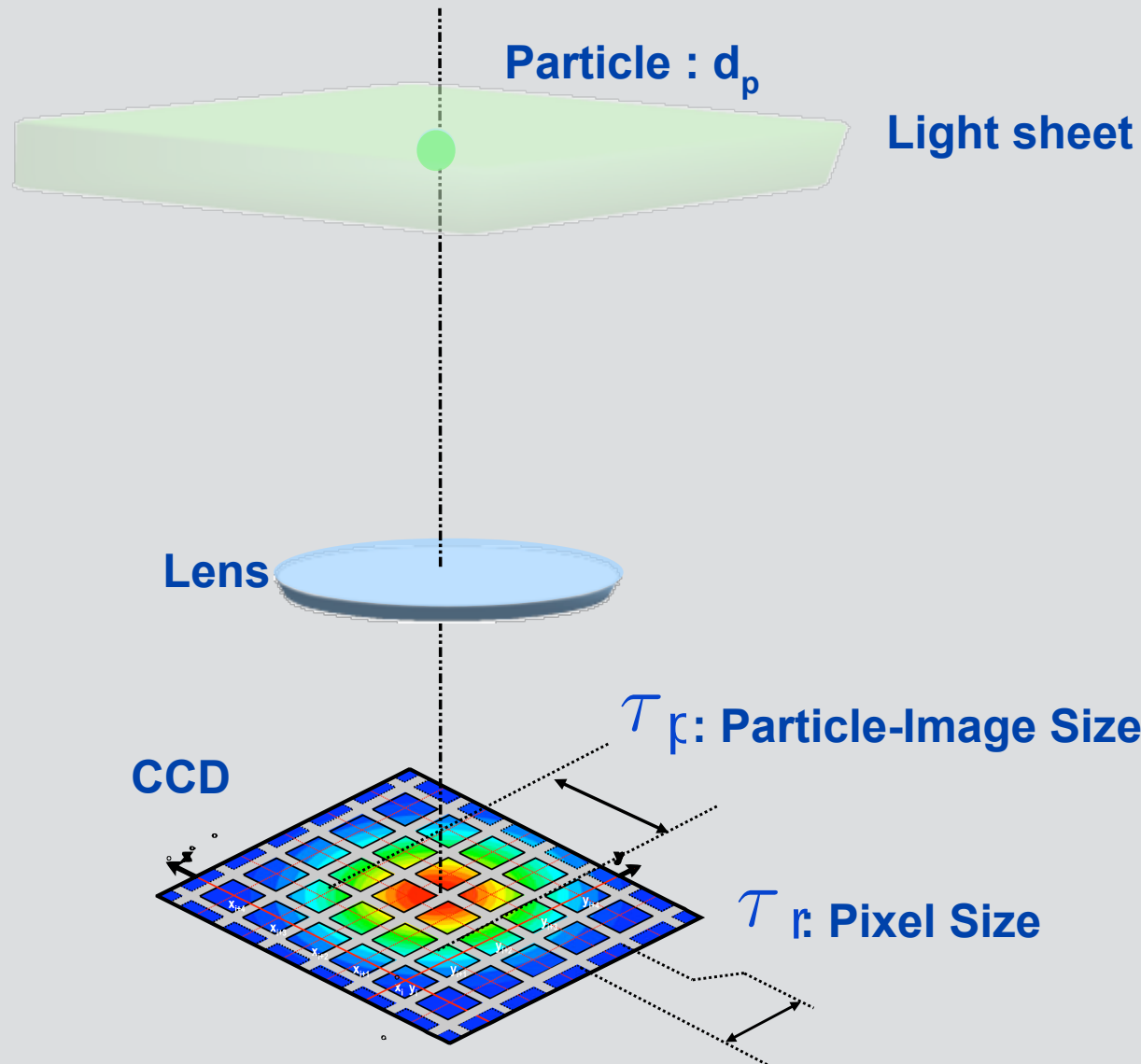
Biais : Important parameters for the peak-locking



● depends on:

- Particle-image diameter
 - Optical setting (magnification, wavelength, f-stop number...)
 - Camera (pixel size, fill factor, micro-lenses...)
 - PIV algorithm (peak-detector, image interpolation scheme...)
- Simple to detect from velocity histogram if bias error > random error
- Peak-locking effect has to be reduce as much as possible during the acquisition processes

Biais : Peak-locking : Particle Image on the CCD



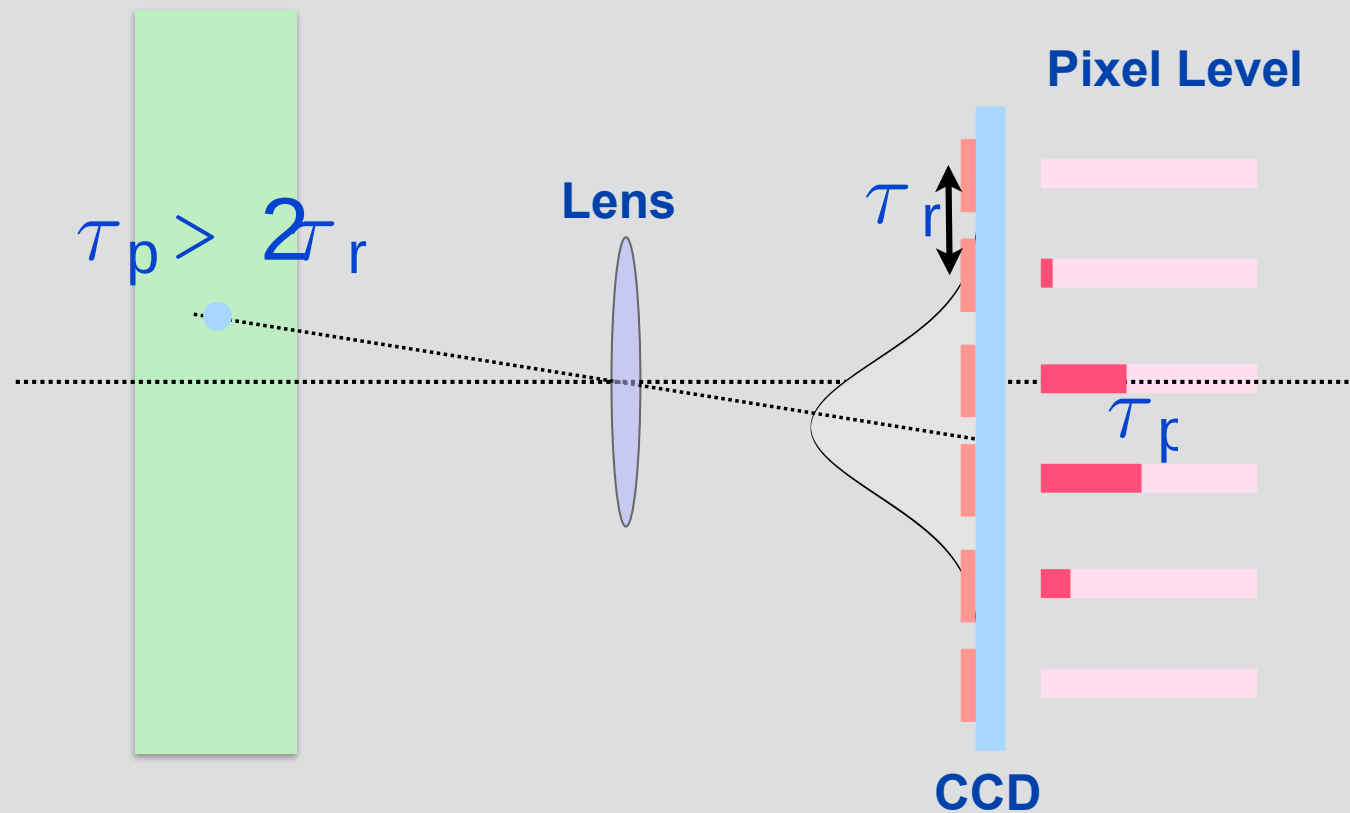
3 cases

$$\tau_p > 2\tau_r$$

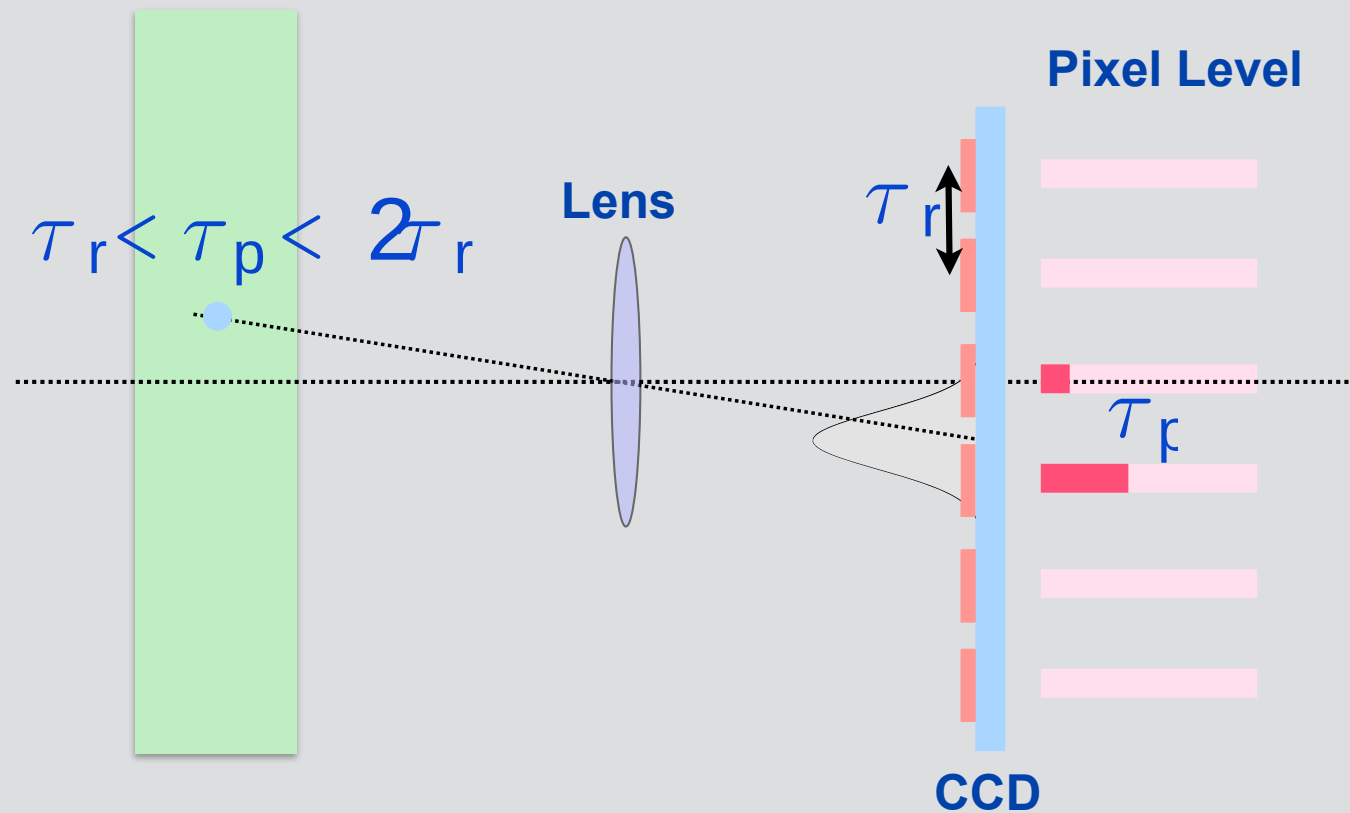
$$\tau_p < \tau_r$$

$$\tau_r < \tau_p < 2\tau_r$$

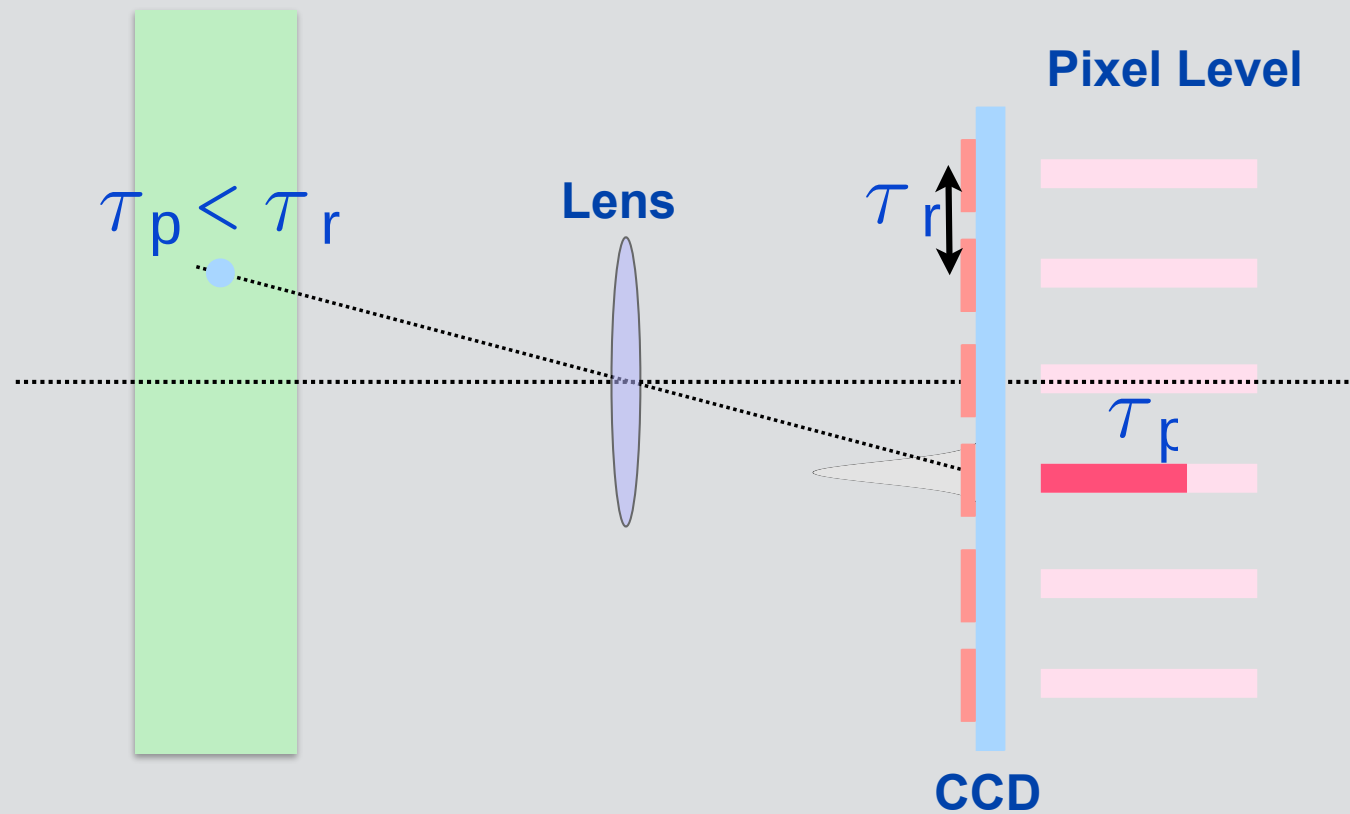
Biais : Peak-locking : Particle-Image Size / Pixel Size



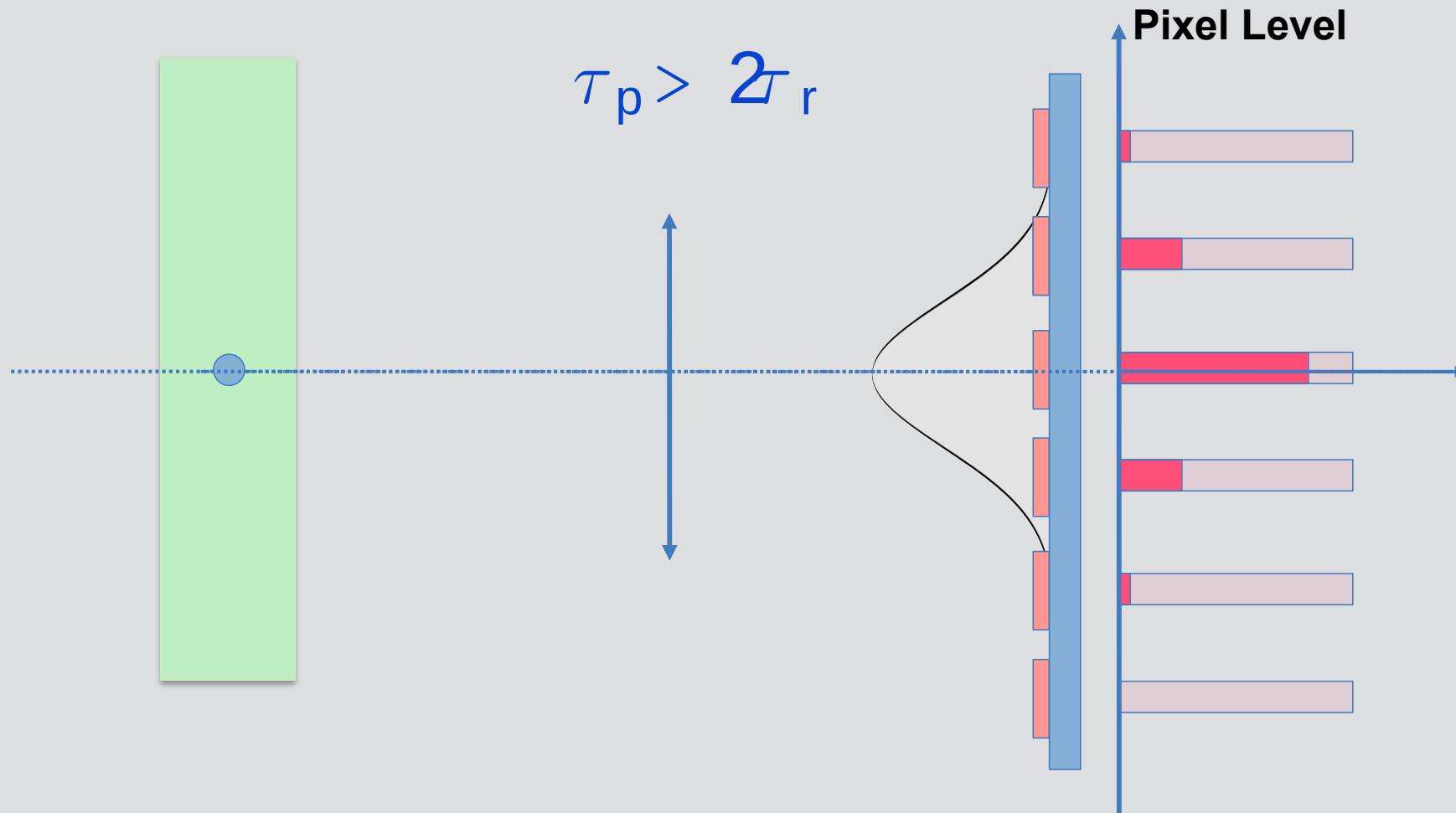
Biais : Peak-locking : Particle-Image Size / Pixel Size



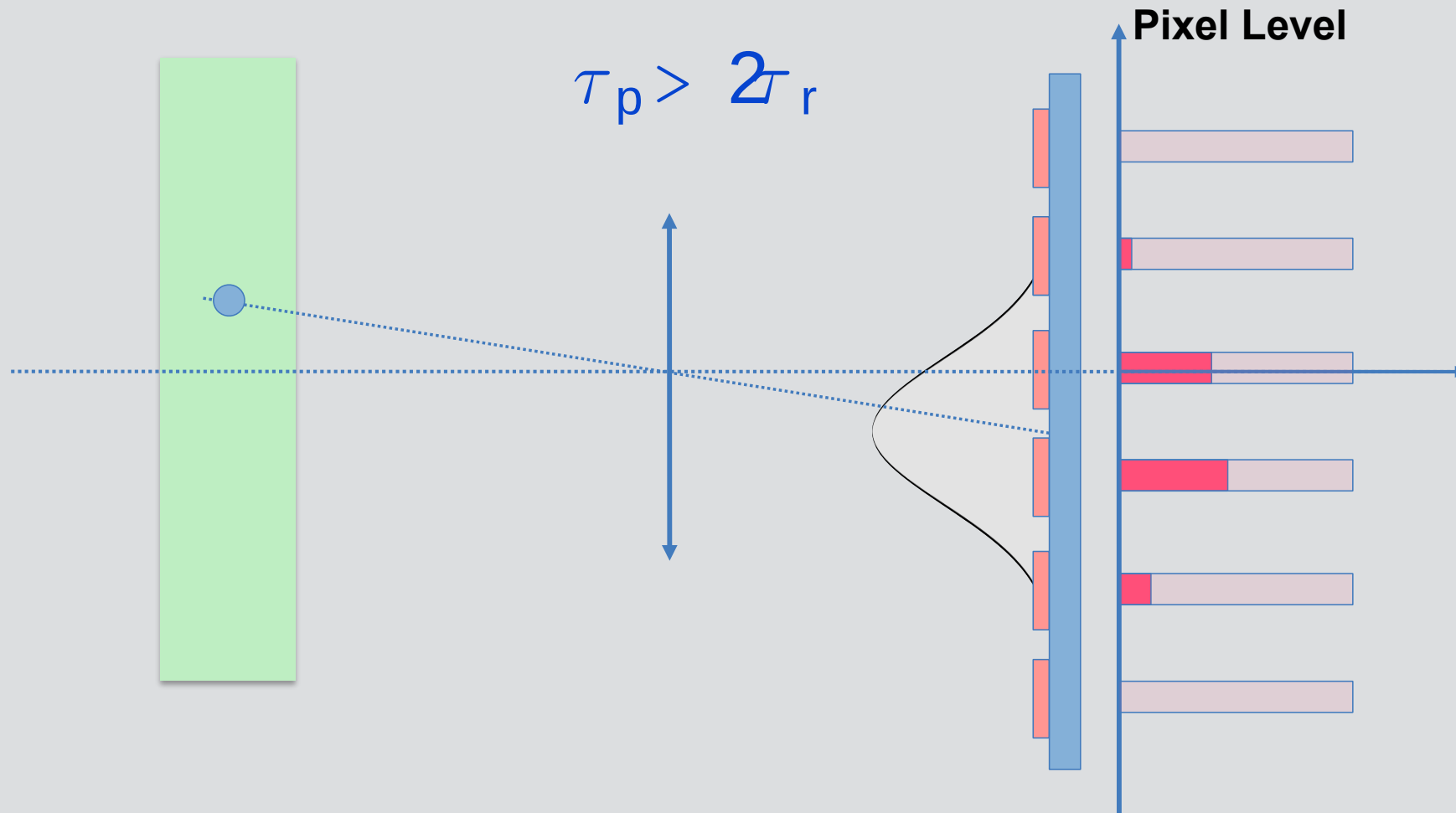
Biais : Peak-locking : Particle-Image Size / Pixel Size



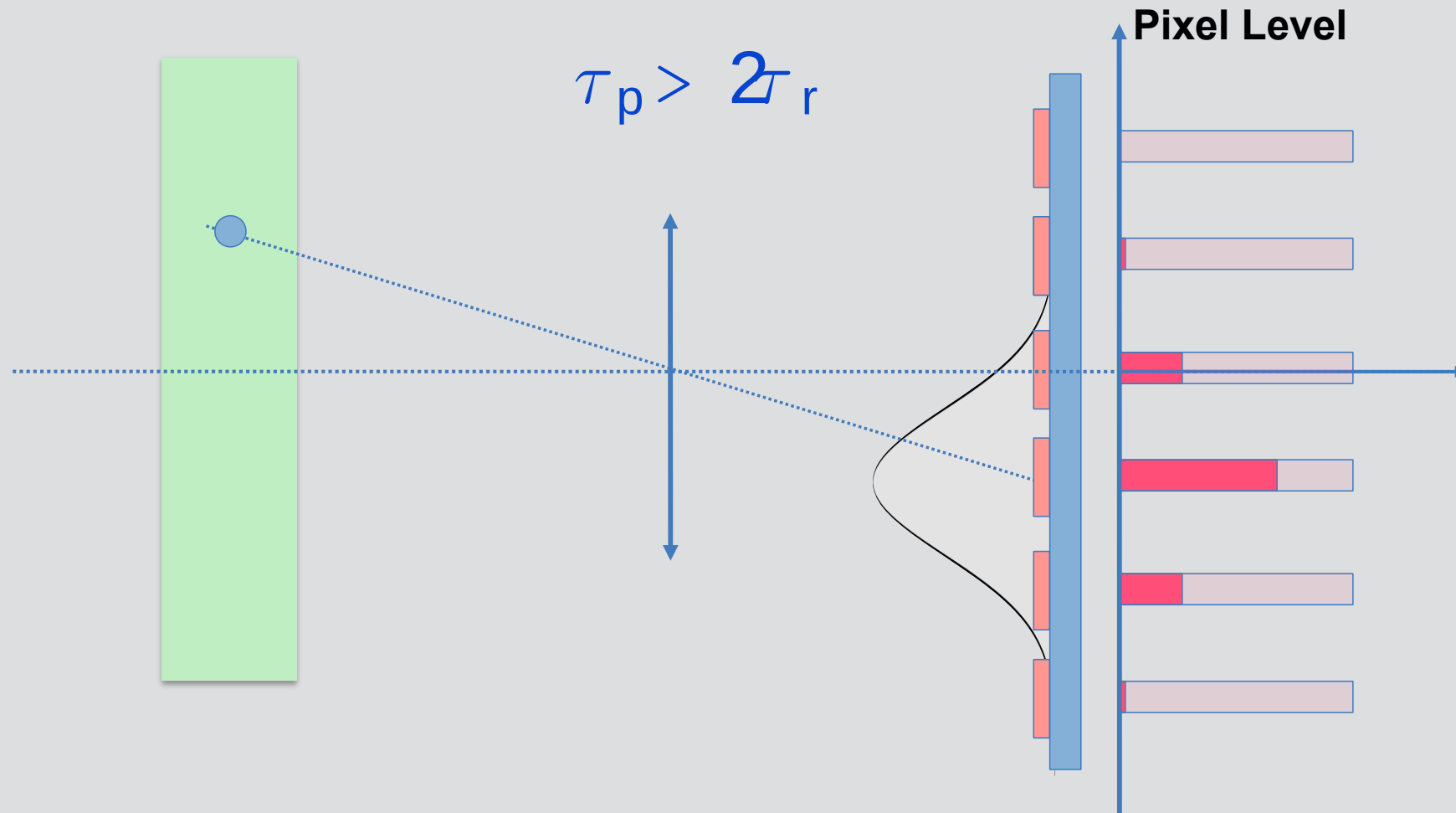
Biais : Peak-locking : Particle-Image Size / Pixel Size



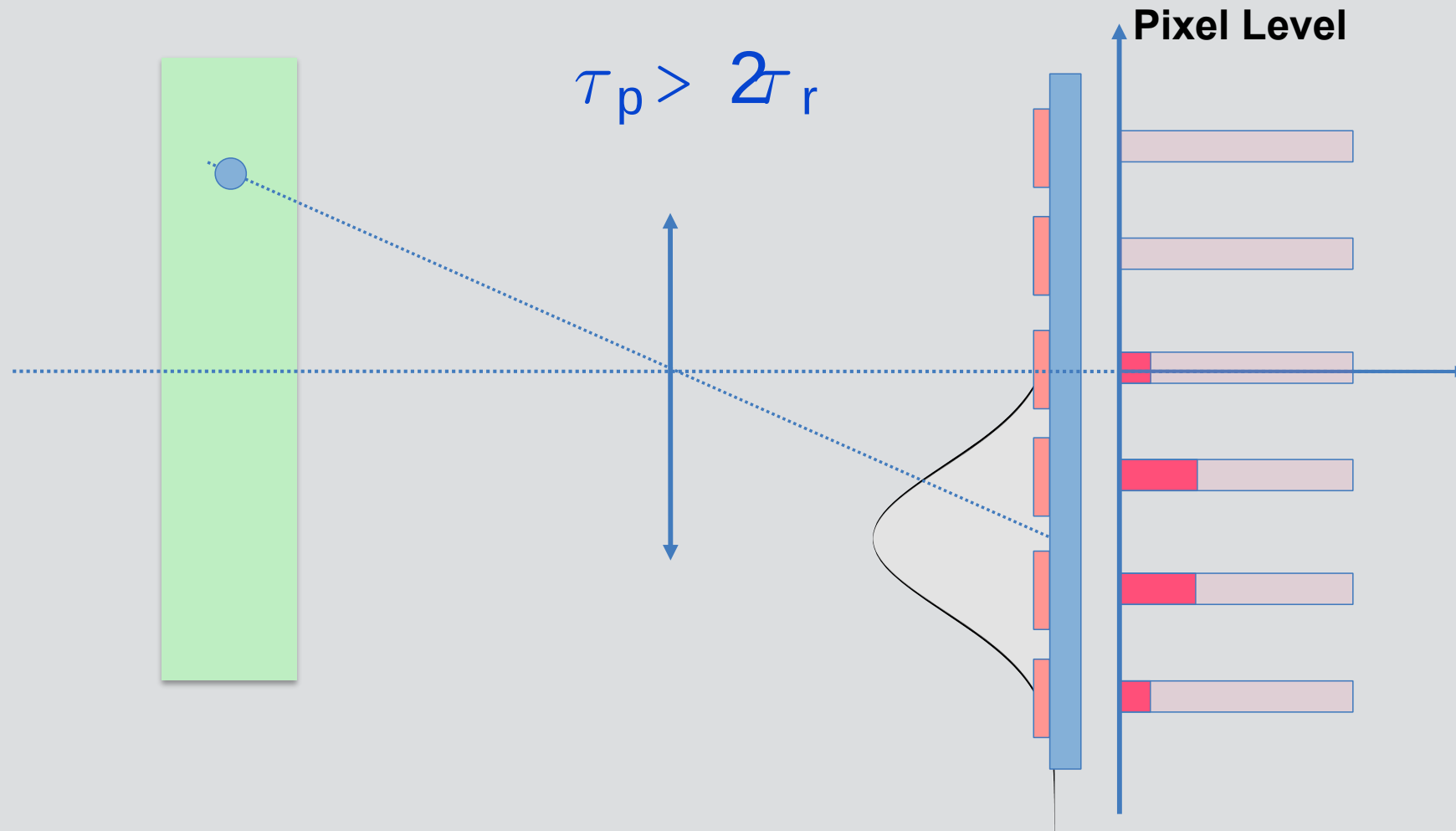
Biais : Peak-locking : Particle-Image Size / Pixel Size



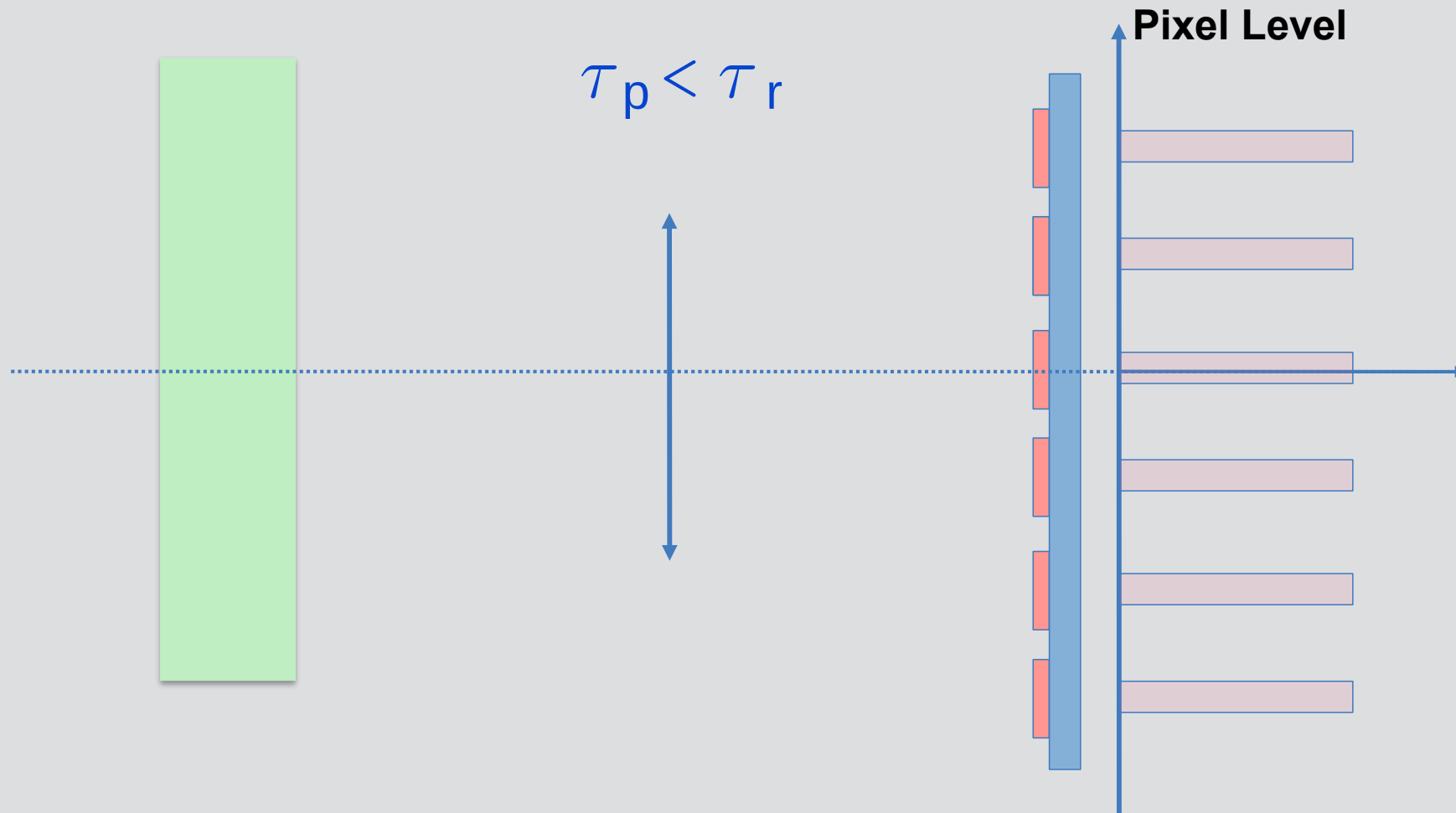
Biais : Peak-locking : Particle-Image Size / Pixel Size



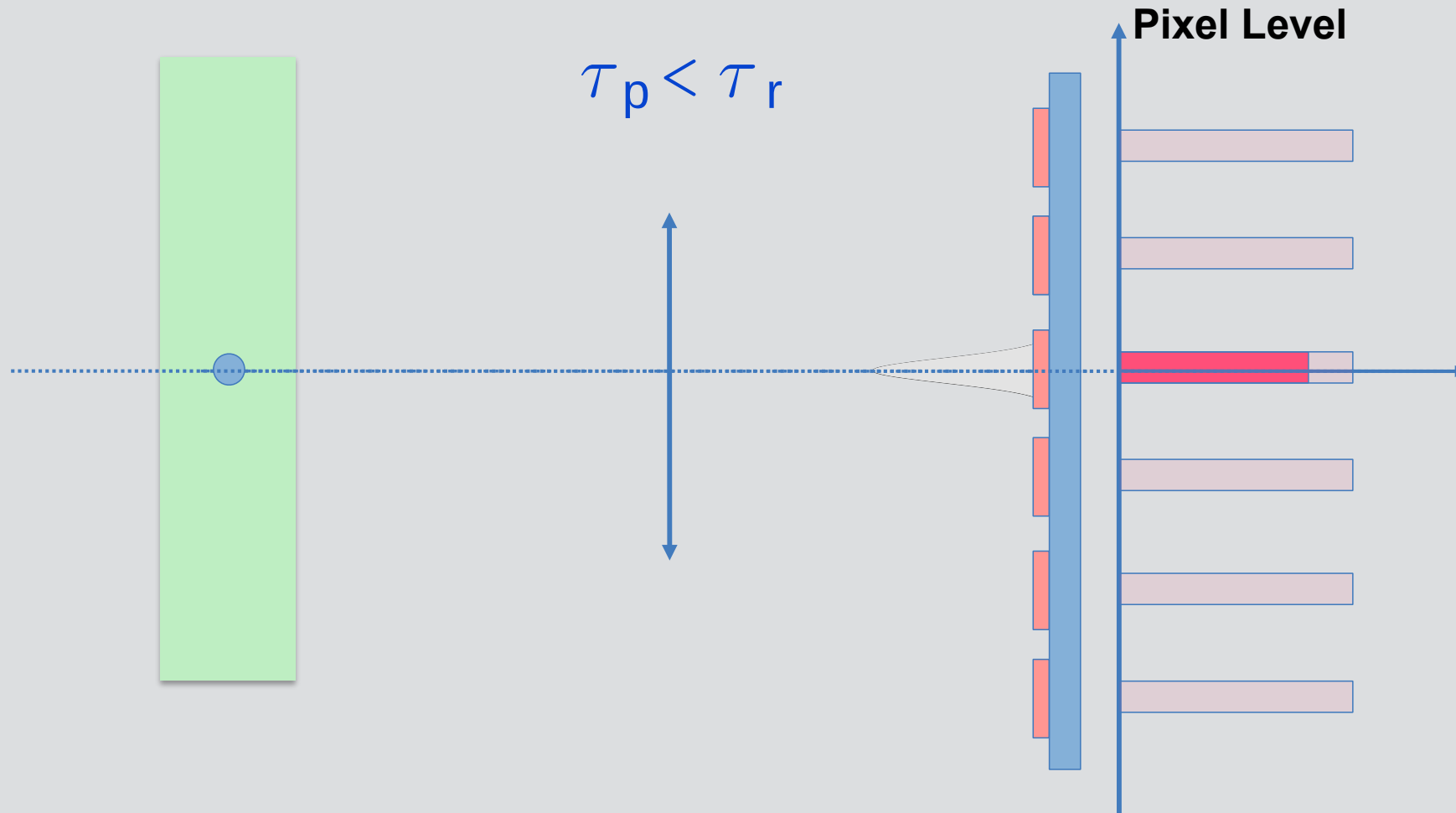
Biais : Peak-locking : Particle-Image Size / Pixel Size



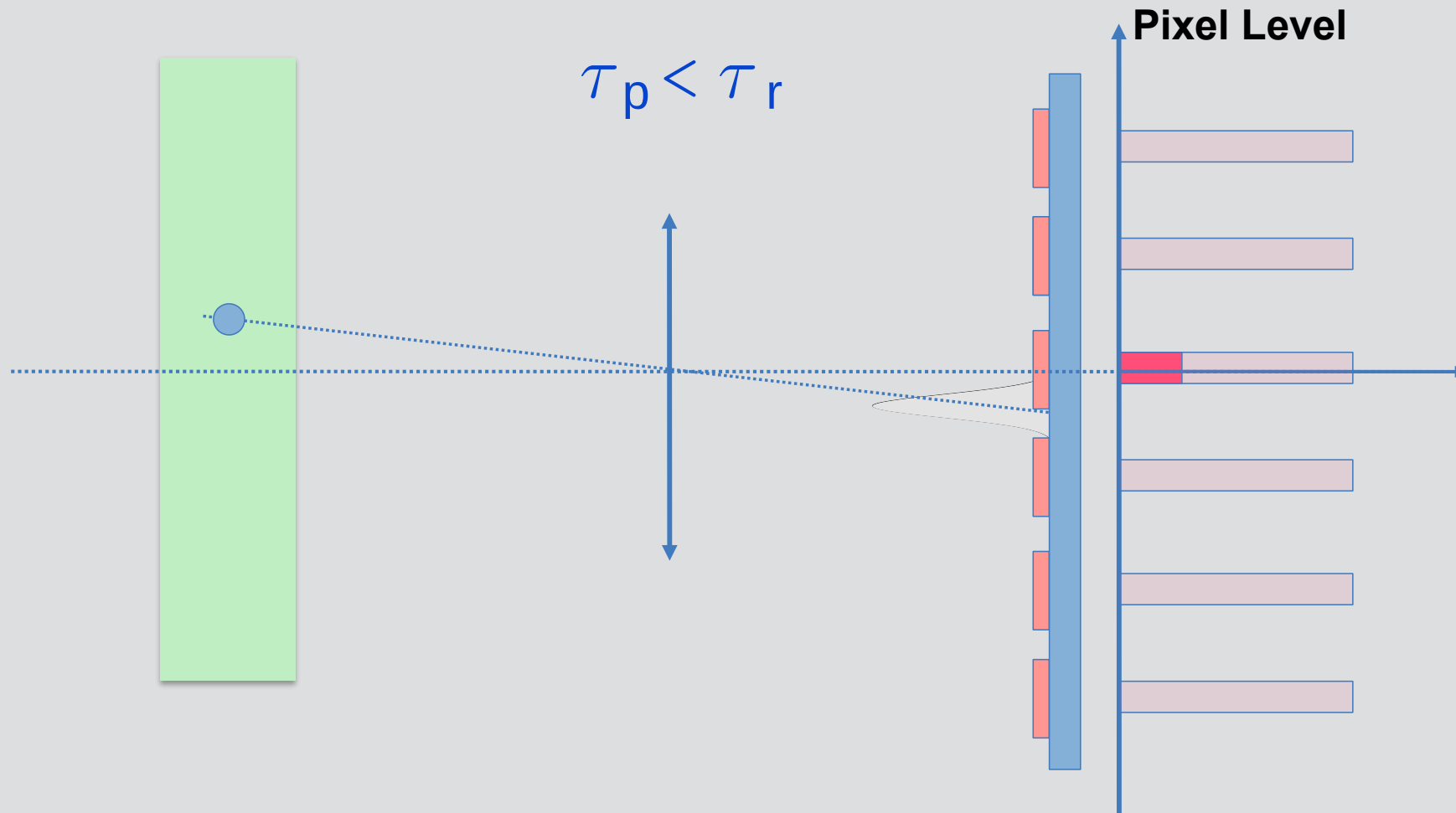
Biais : Peak-locking : Particle-Image Size / Pixel Size



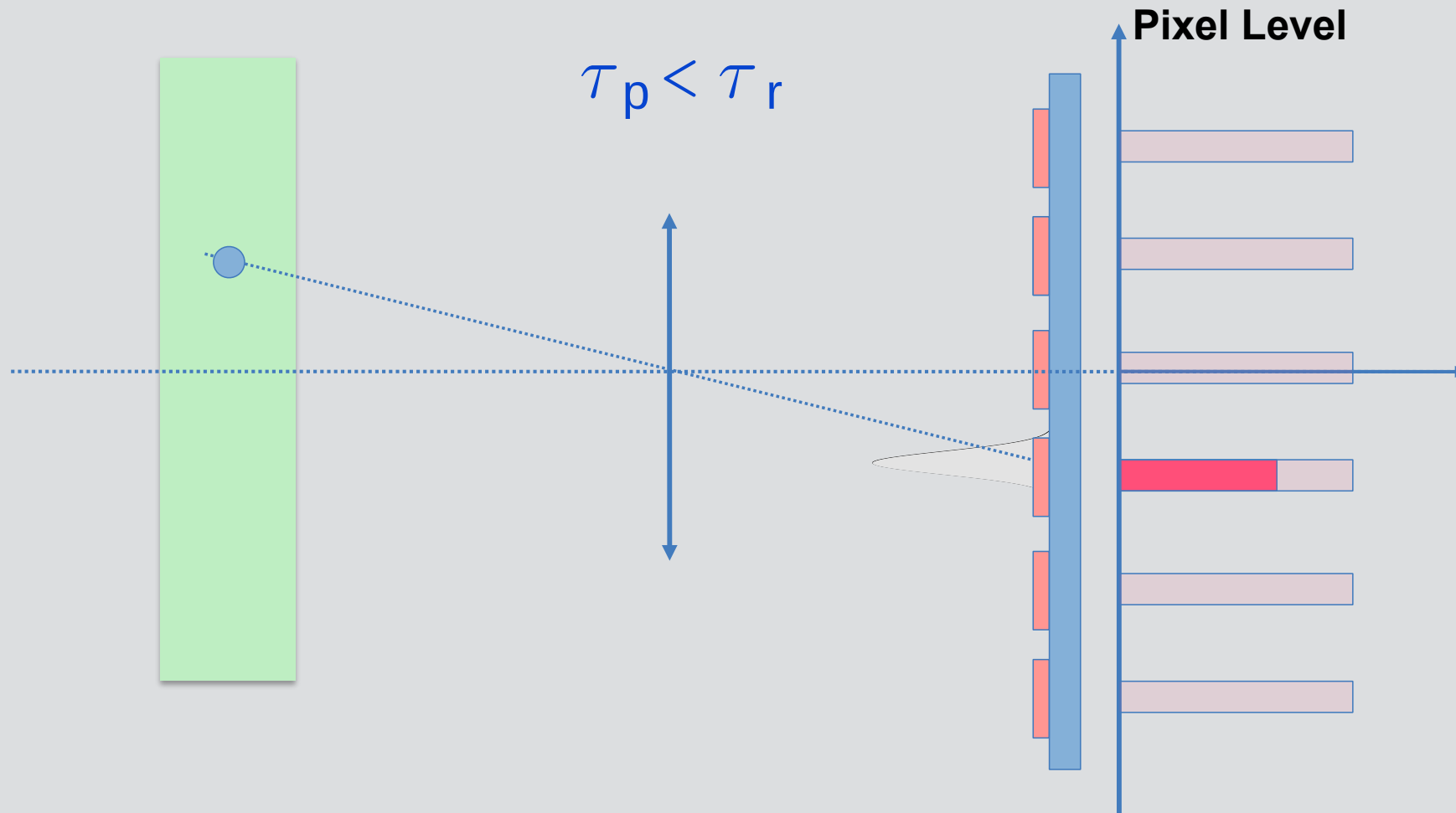
Biais : Peak-locking : Particle-Image Size / Pixel Size



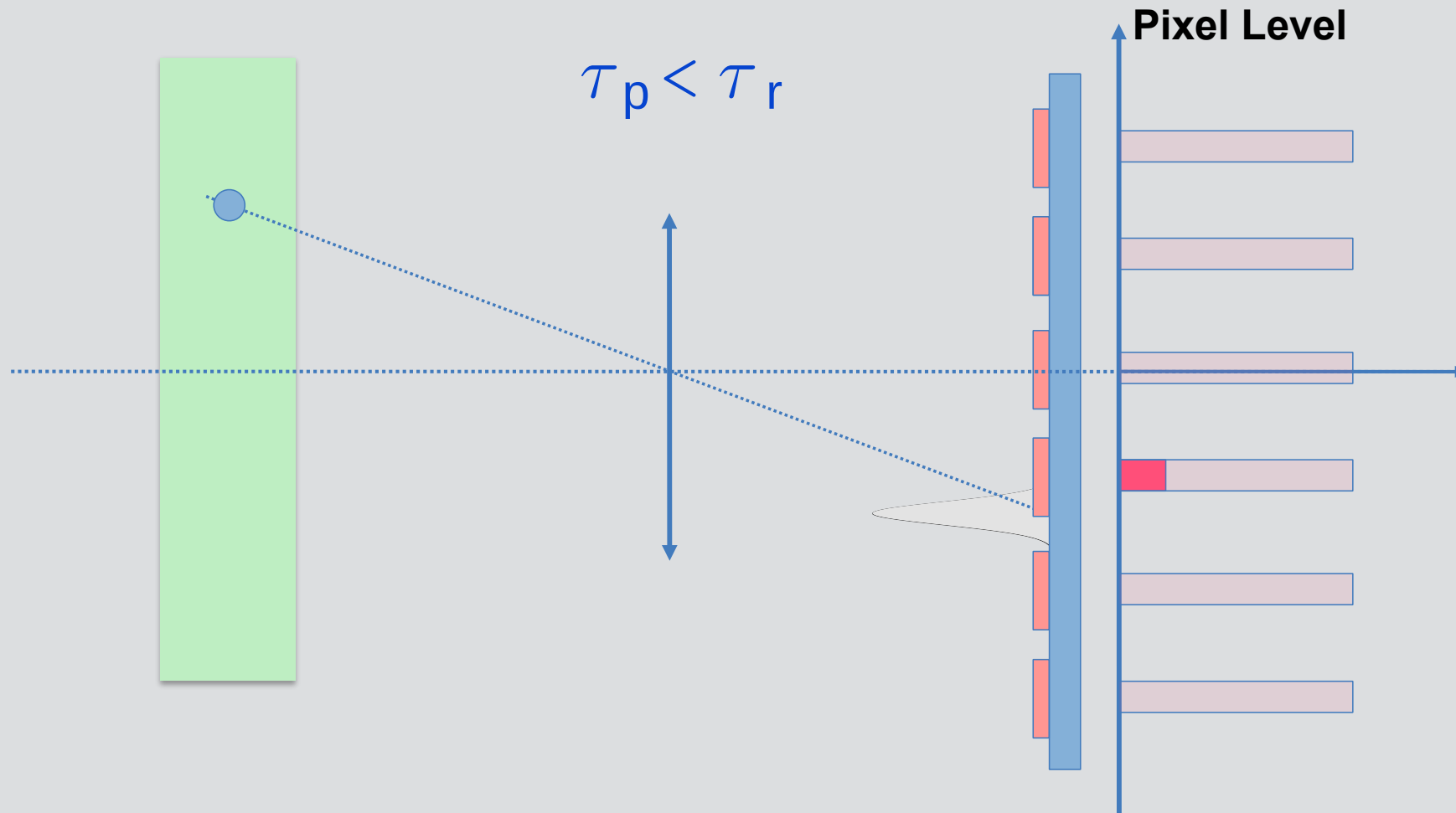
Biais : Peak-locking : Particle-Image Size / Pixel Size



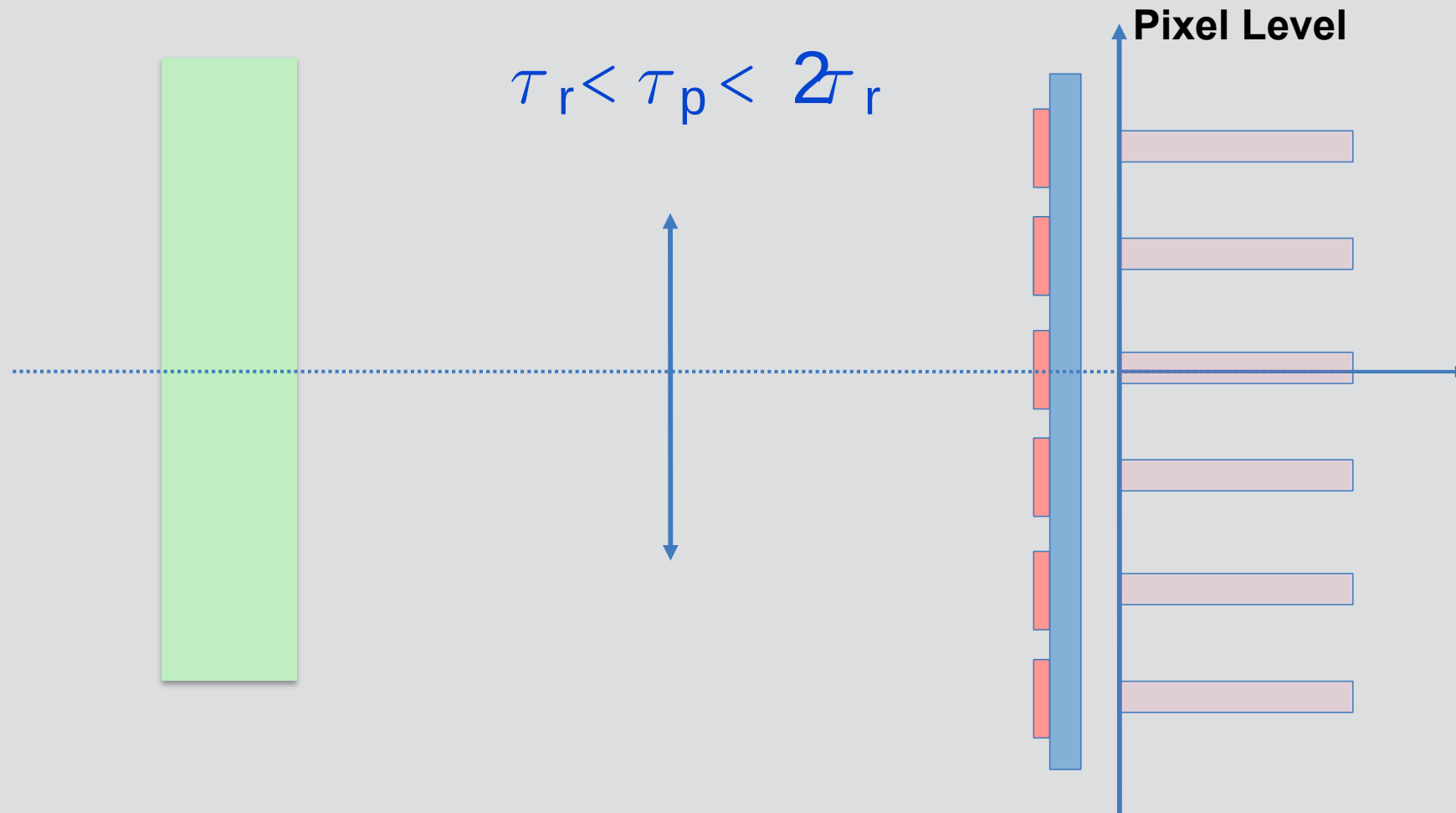
Biais : Peak-locking : Particle-Image Size / Pixel Size



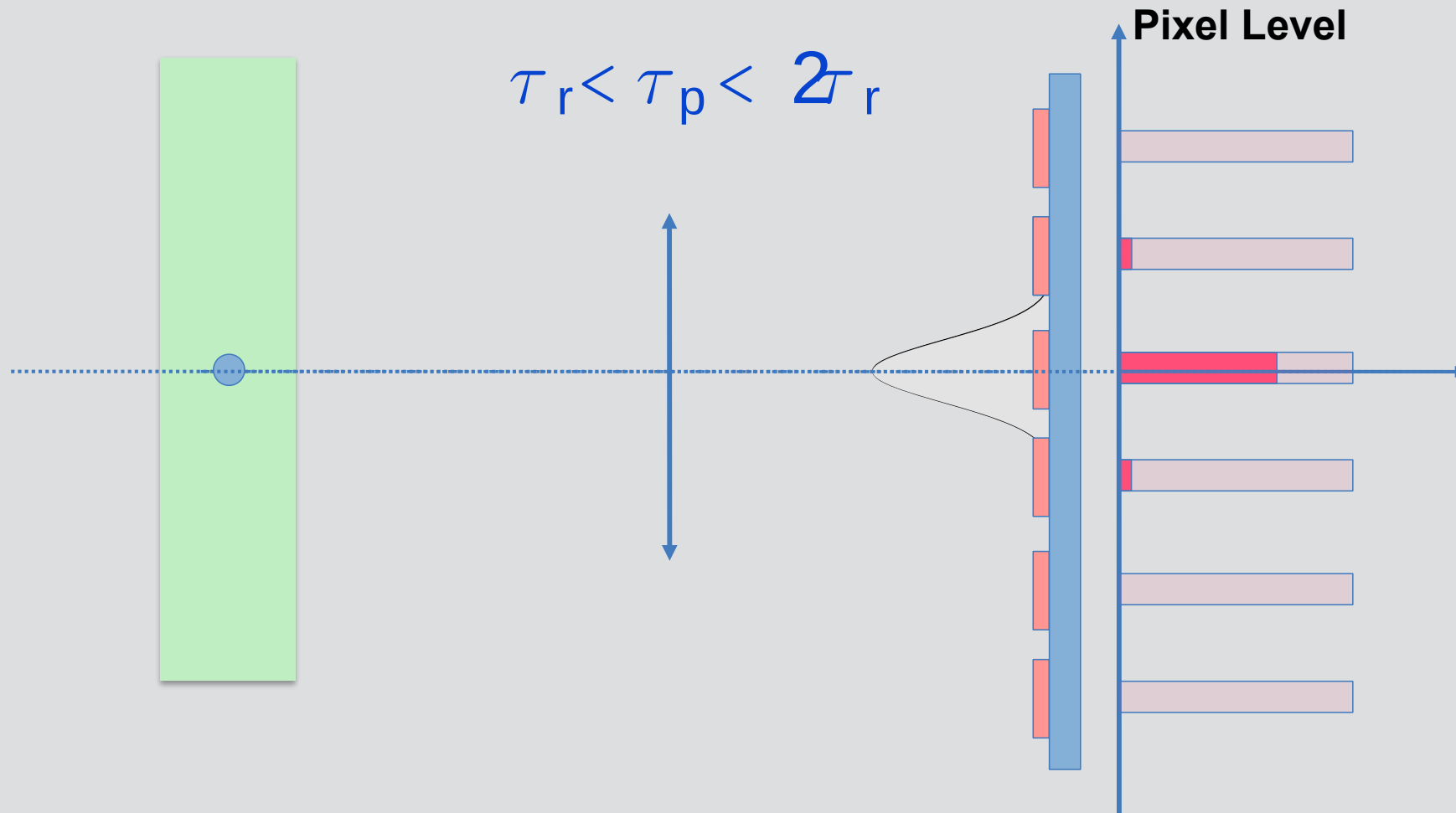
Biais : Peak-locking : Particle-Image Size / Pixel Size



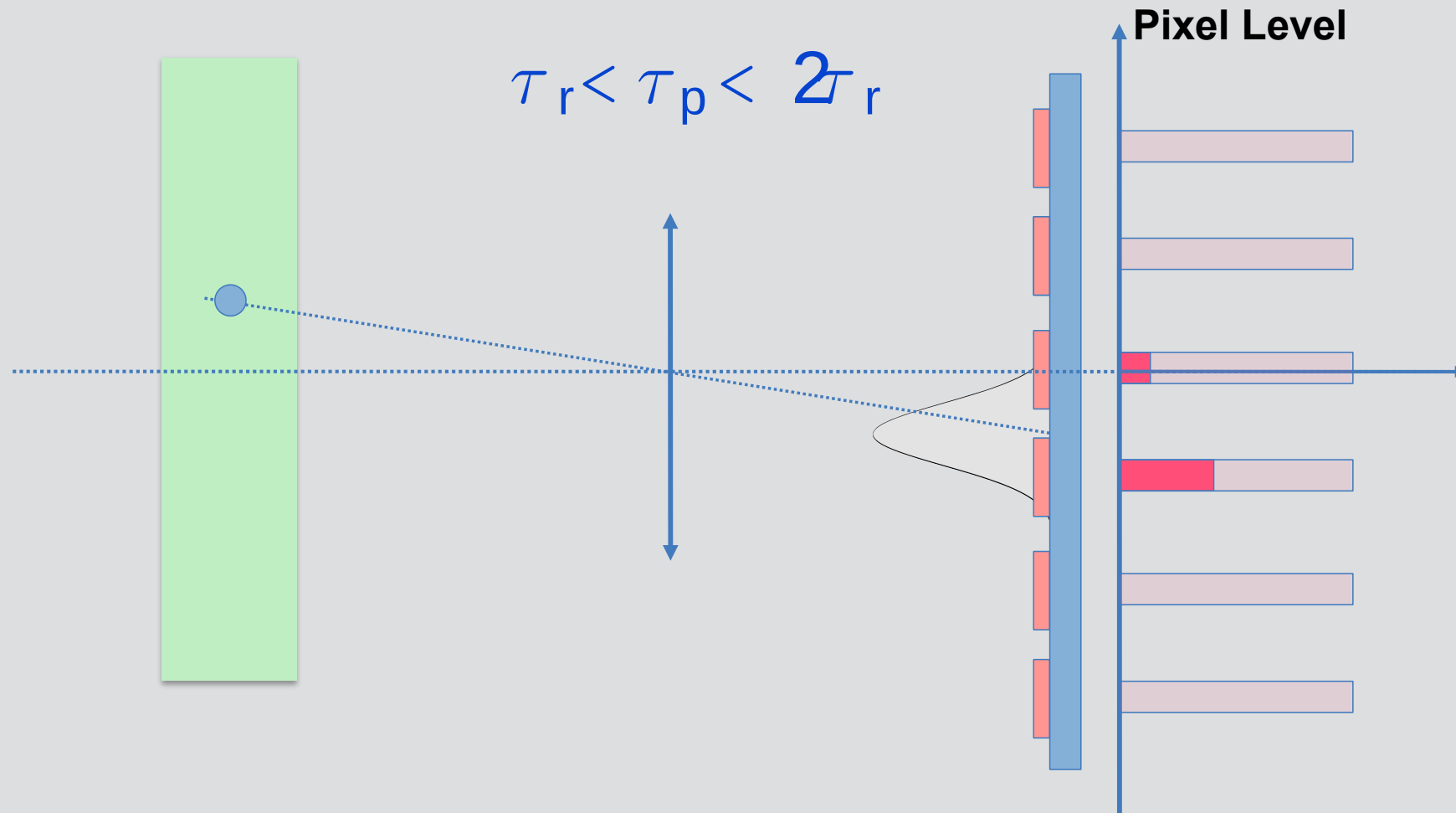
Biais : Peak-locking : Particle-Image Size / Pixel Size



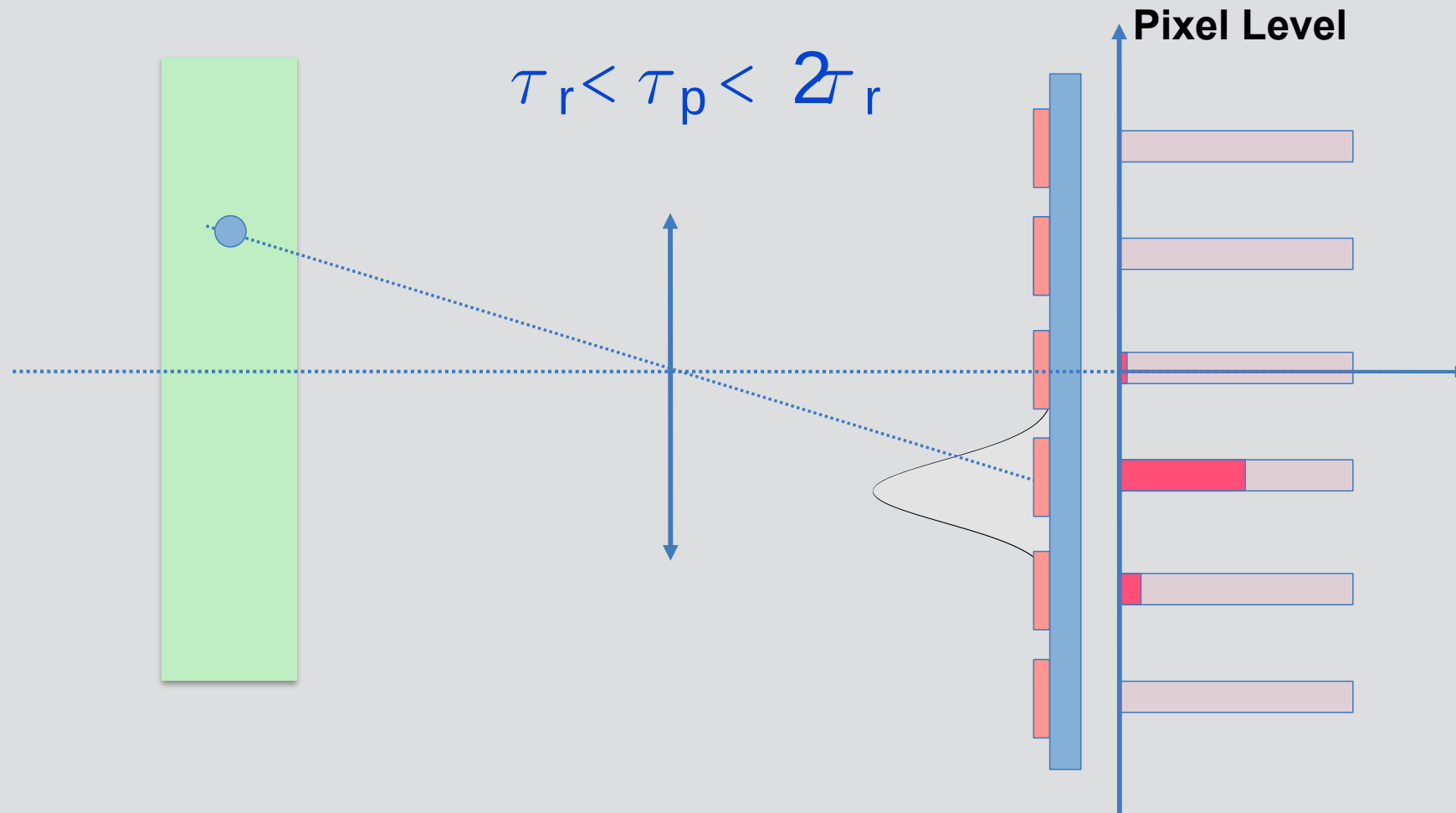
Biais : Peak-locking : Particle-Image Size / Pixel Size



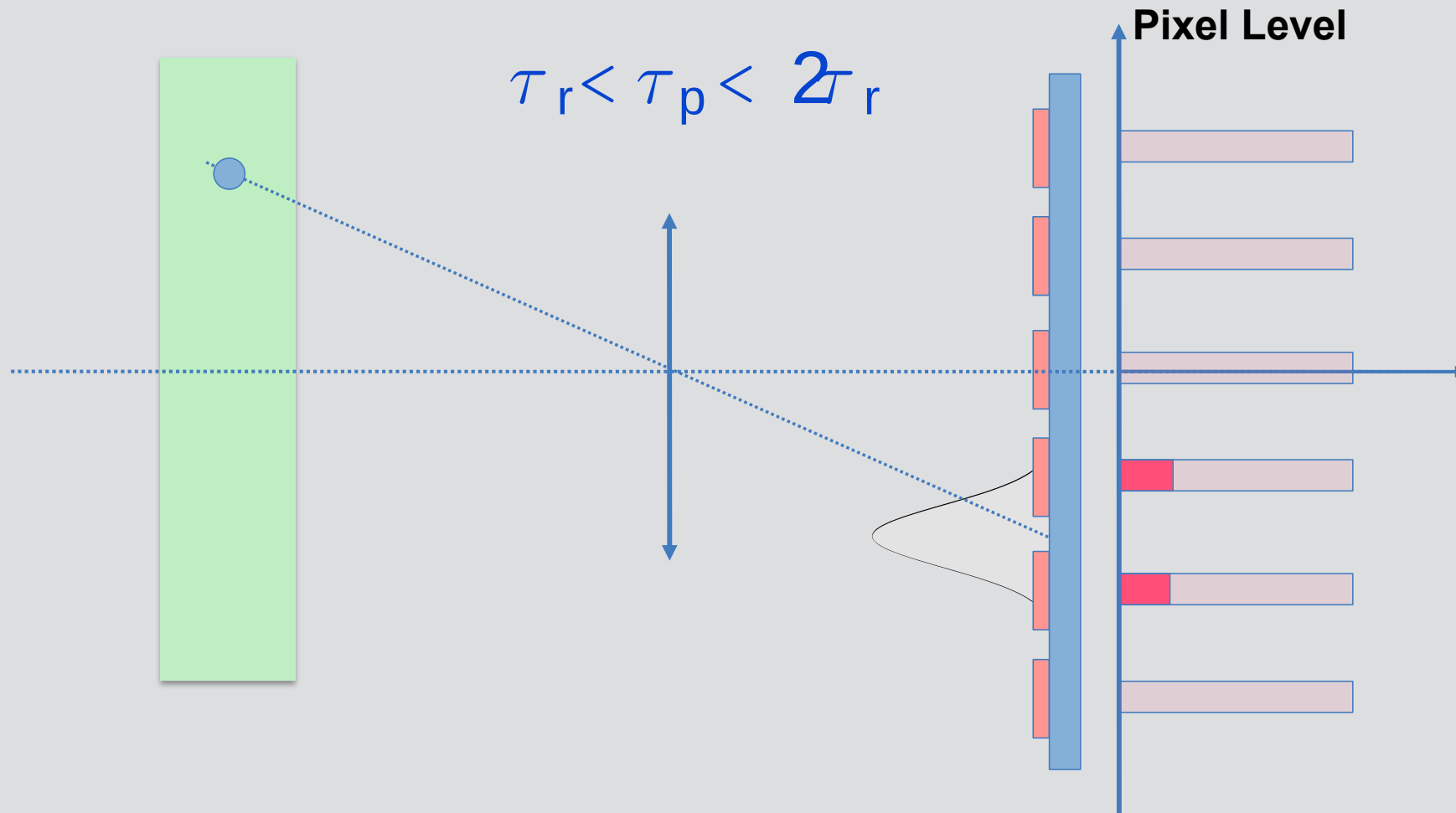
Biais : Peak-locking : Particle-Image Size / Pixel Size



Biais : Peak-locking : Particle-Image Size / Pixel Size



Biais : Peak-locking : Particle-Image Size / Pixel Size

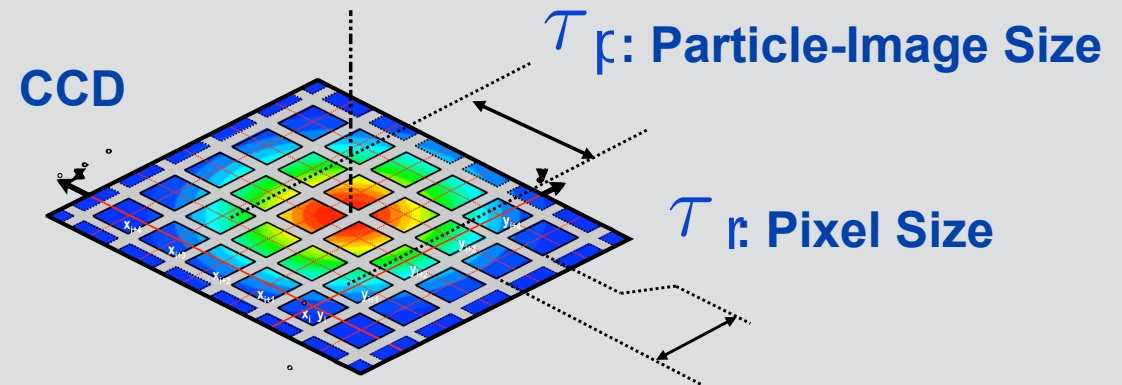


Biais : Peak-locking – Important parameters

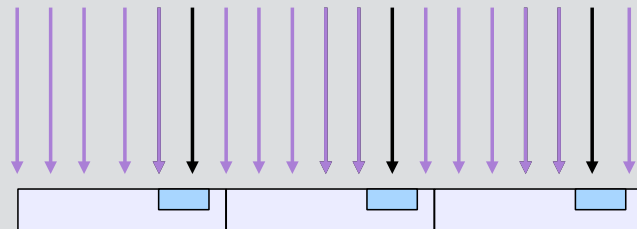
● Particle-image diameter

● Pixel Size

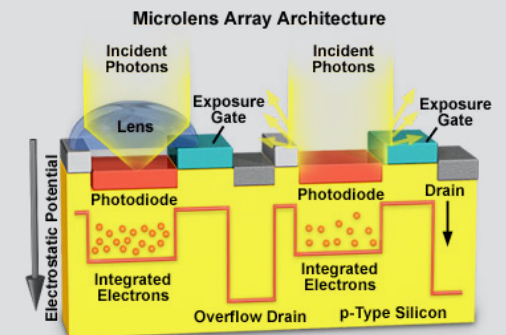
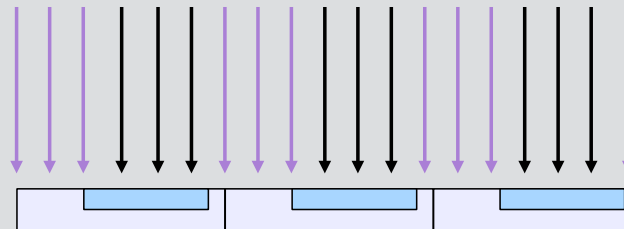
● Fill factor of CCD



Low fill factor

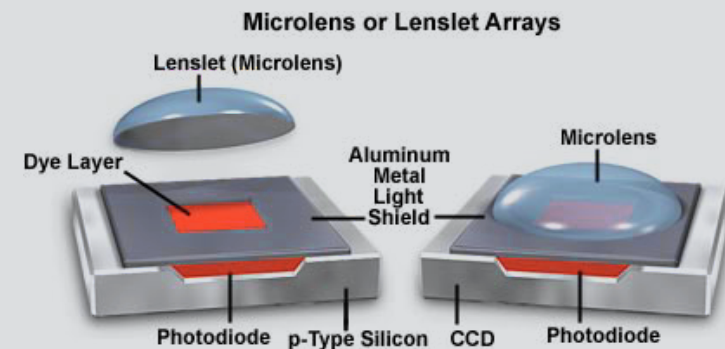
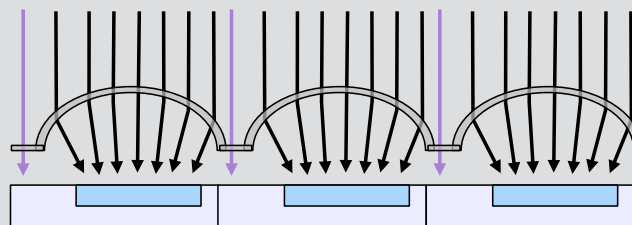


High fill factor



● Spatially varying illumination response

Micro lenses



Biais : Peak-locking : How to reduce peak-locking effect

● PIV Algorithm

$$\tau_r < \tau_p < 2\tau_r$$

- Peak-detector
- Continuous Window Shift (CWS) or Image Deformation techniques (PID)
 - Image Interpolation scheme
- Pre-processing of images

● During acquisition

$$\tau_p < \tau_r$$

- Adjustment of the acquisition parameters
 - Pixel size
 - (5 to 10 μm for PIV standard cameras)
 - (10 to 25 μm for PIV high speed cameras)
 - Changing de particle-image size
 - f-stop number
 - De-focusing



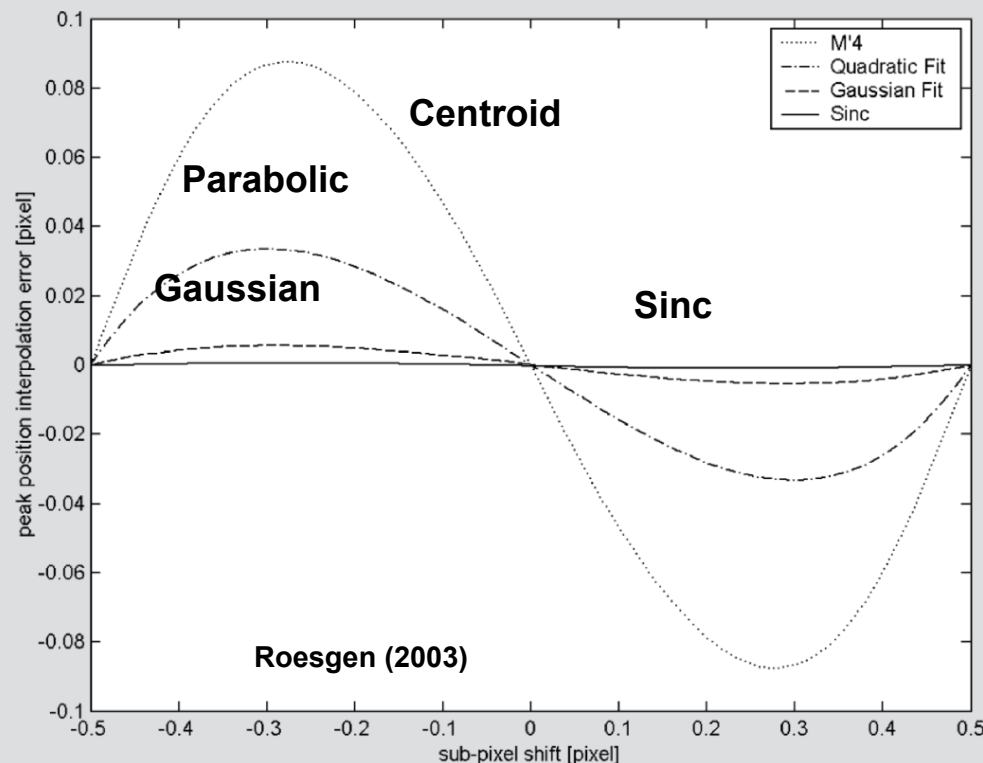
Biais : Peak-locking : How to reduce peak-locking effect

PIV Algorithm

- Peak-detector
- Continuous Window Shift (CWS) or Image Deformation techniques (PID)
 - Image Interpolation scheme
- Pre-processing of images

$$\tau_r < \tau_p < 2\tau_r$$

Bias error



Biais : Peak-locking : How to reduce peak-locking effect

PIV Algorithm

Peak-detector

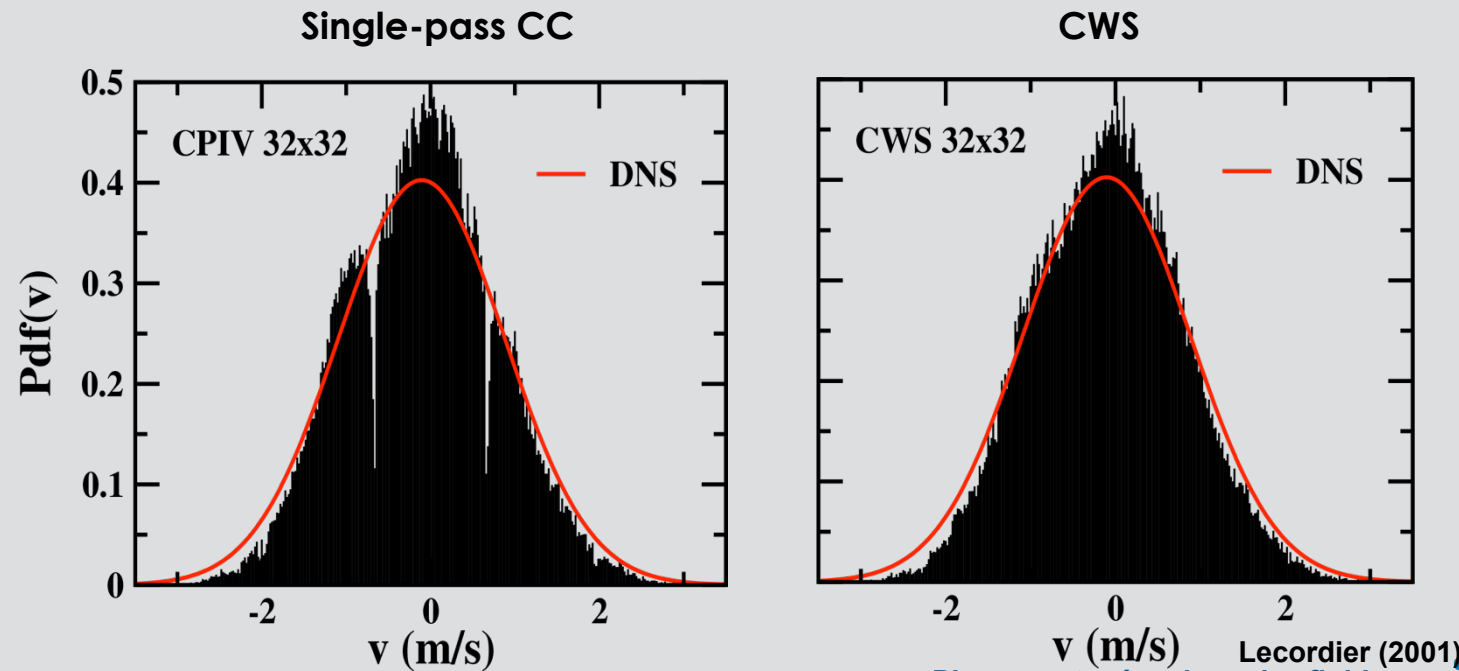
Continuous Window Shift (CWS) or Image Deformation techniques (PID)

Image Interpolation scheme

Pre-processing of images

$$\tau_r < \tau_p < 2\tau_r$$

Simulation



Biais : Peak-locking : How to reduce peak-locking effect

PIV Algorithm

Peak-detector

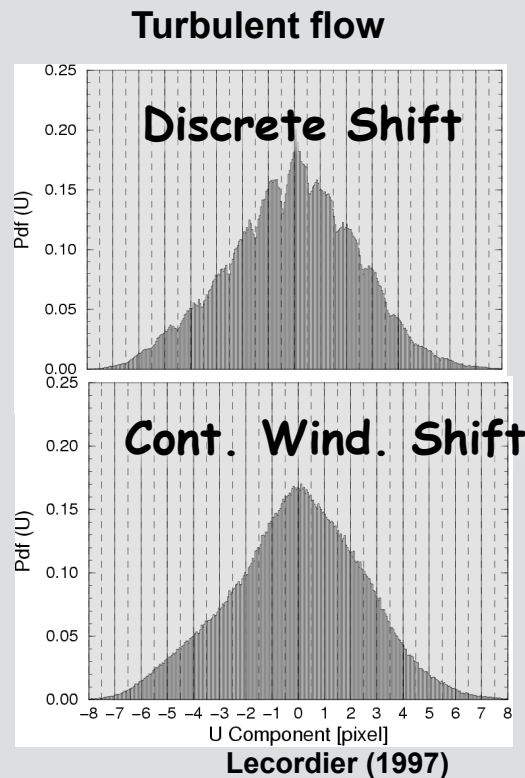
Continuous Window Shift (CWS) or Image Deformation techniques (PID)

Image Interpolation scheme

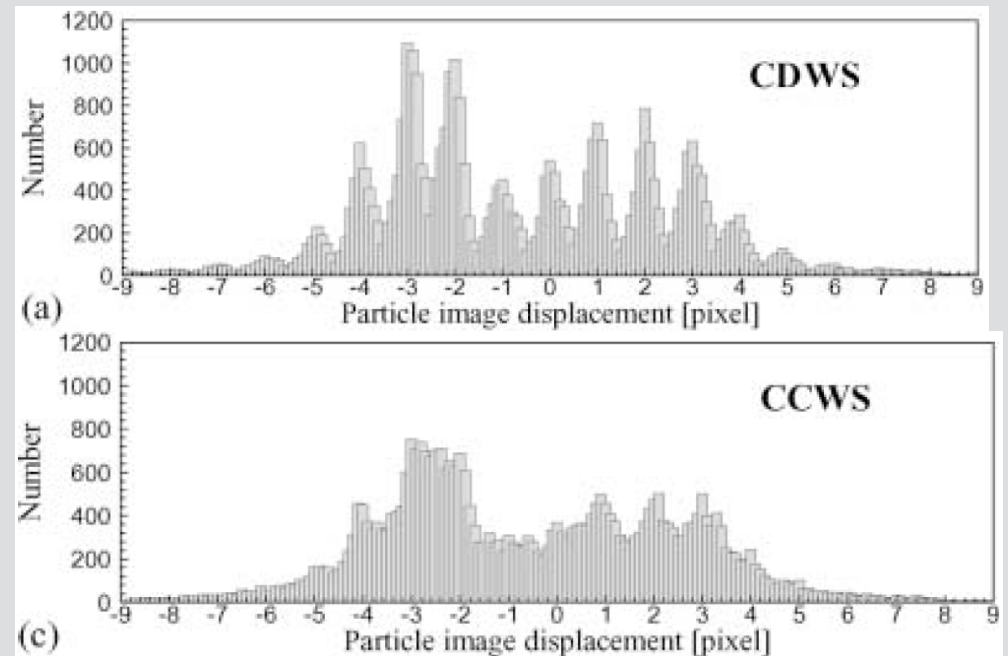
Pre-processing of images

$$\tau_r < \tau_p < 2\tau_r$$

Experiments



Thermal convection flow



Biais : Peak-locking : How to reduce peak-locking effect

PIV Algorithm

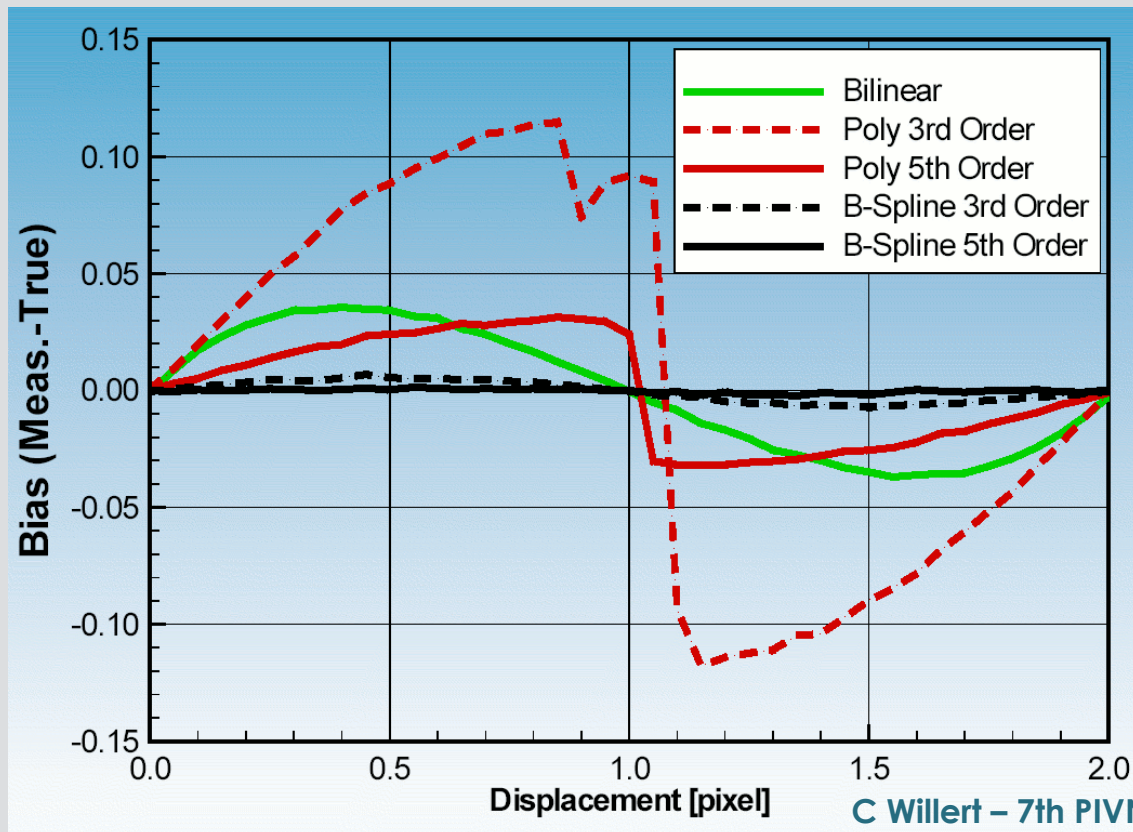
Peak-detector

Continuous Window Shift (CWS) or Image Deformation techniques (PID)

Image Interpolation scheme

Pre-processing of images

$$\tau_r < \tau_p < 2\tau_r$$



Simulation parameters:

- 3x3 Gaussian peak-fit
- 4 px particle image diameter
- constant y-shift : 0.5 px
- symmetric image-deformation with 4 iterations
- image density ~0.1/px

C Willert – 7th PIVNET workshop – July 9th & 10th 2004

Biais : Peak-locking : How to reduce peak-locking effect

PIV Algorithm

- Peak-detector
- Continuous Window Shift (CWS) or Image Deformation techniques
 - Image Interpolation scheme
- Pre-processing of images

$$\tau_r < \tau_p < 2\tau_r$$



NO ADDITION OF PARASITIC DISPLACEMENTS

Biais : Peak-locking : How to reduce peak-locking effect

● During acquisition

$$\tau_p < \tau_r$$

● Adjustment of the acquisition parameters

● Pixel size

- (5 to 10 μm for PIV standard cameras)
- (10 to 25 μm for PIV high speed cameras)

● Changing de particle-image size

- De-focusing - decrease the peak-locking but increase the random noise
- F-stop number

Biais : Peak-locking : How to reduce peak-locking effect

● During acquisition

$$\tau_p < \tau_r$$

● Adjustment of the acquisition parameters

● Pixel size

- (5 to 10 μm for PIV standard cameras)
- (10 to 25 μm for PIV high speed cameras)

● Changing de particle-image size

- De-focusing - decrease the peak-locking but increase the random noise
- F-stop number



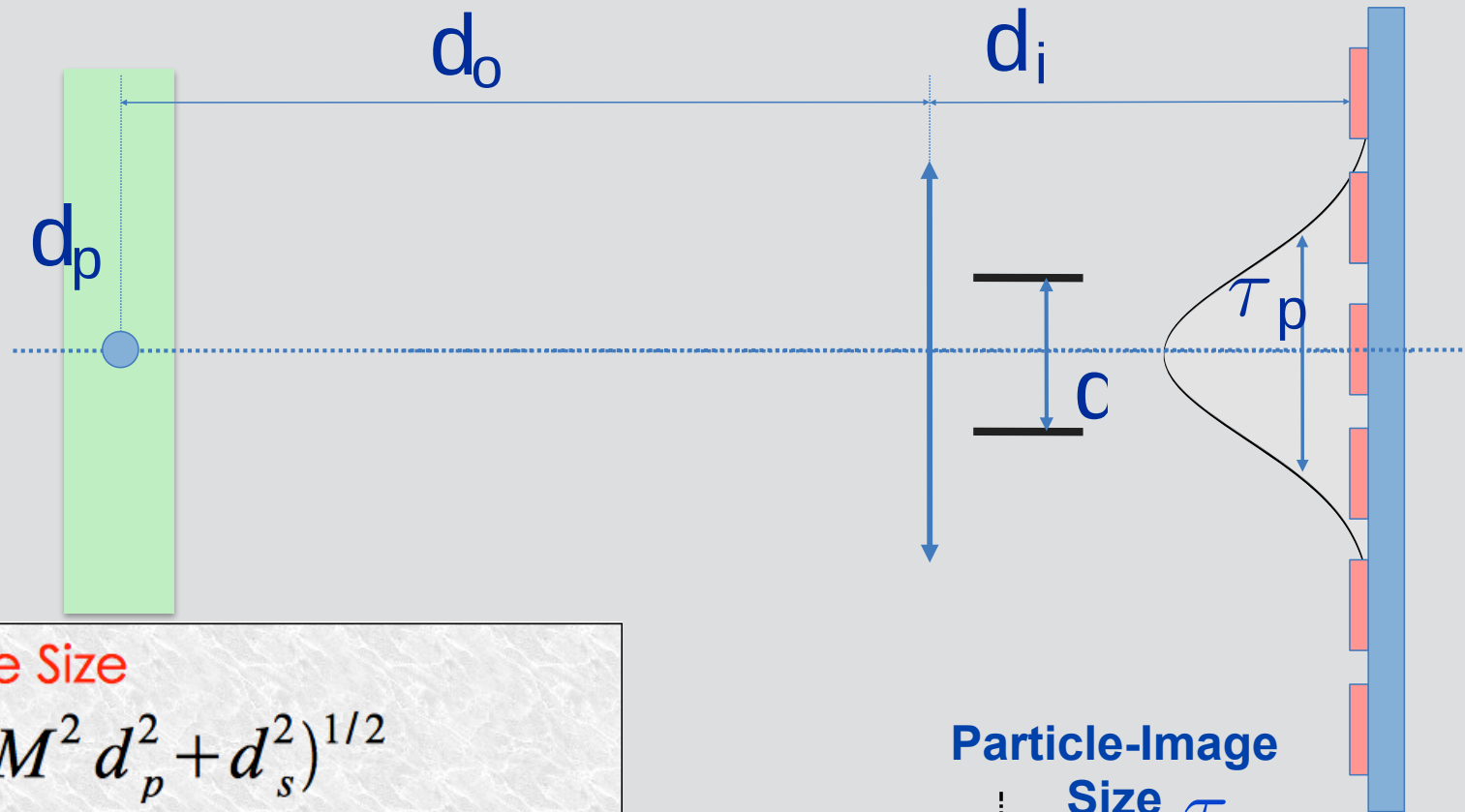
Good solution

But conceivable only with powerful laser to maintain significant signal intensity to avoid to increase the random noise

Problem with High speed PIV System

Pixel Size : 10 to 25 μm for PIV high speed cameras
High speed laser : 10 to 40 mJ/pulse @ 2kHz

Biais : Peak-locking : Particle image-diameter / f-stop number



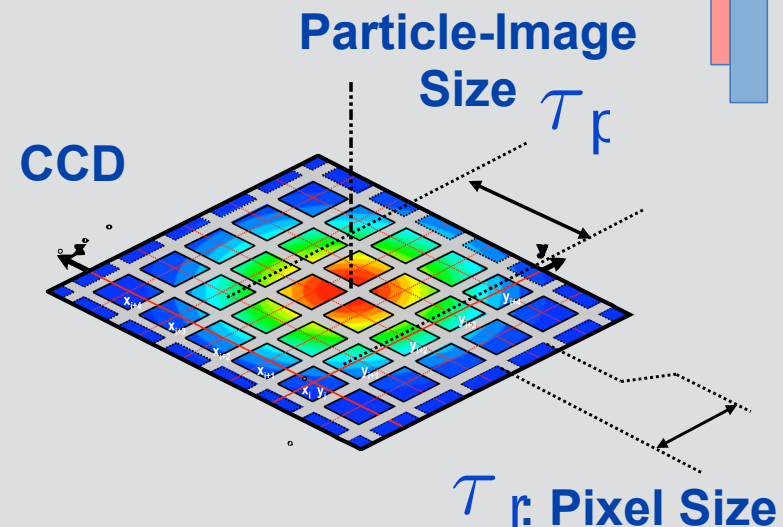
Particle Image Size

$$\tau_p = (M^2 d_p^2 + d_s^2)^{1/2}$$

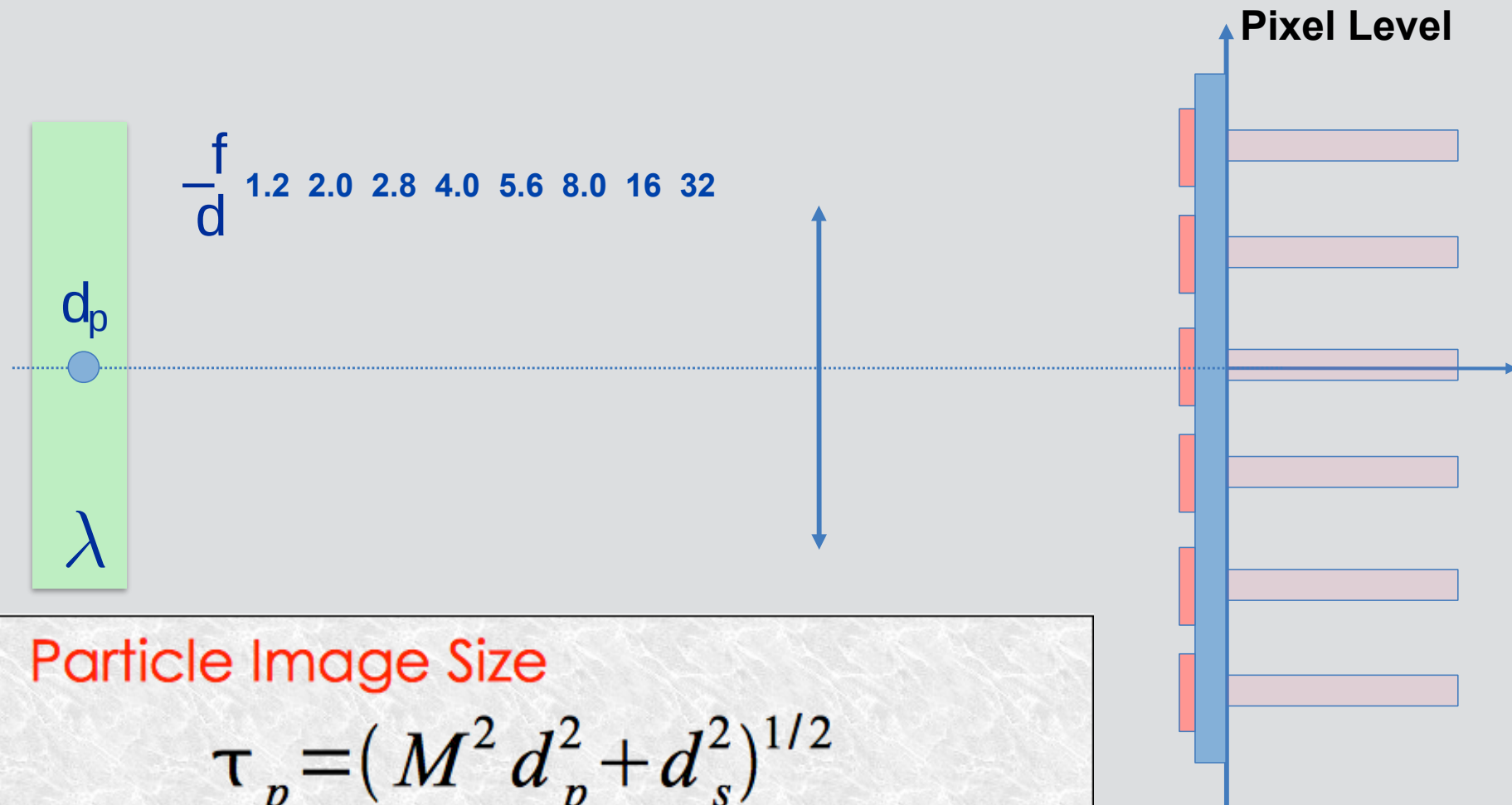
$$d_s = 2.44(M+1)\lambda \frac{f}{d} \quad \text{Diffraction spot}$$

$$\frac{f}{d} \quad \text{F-stop number}$$

$$M = \frac{d_i}{d_o} \quad \text{Optical magnification}$$



Biais : Peak-locking : Particle image-diameter / f-stop number

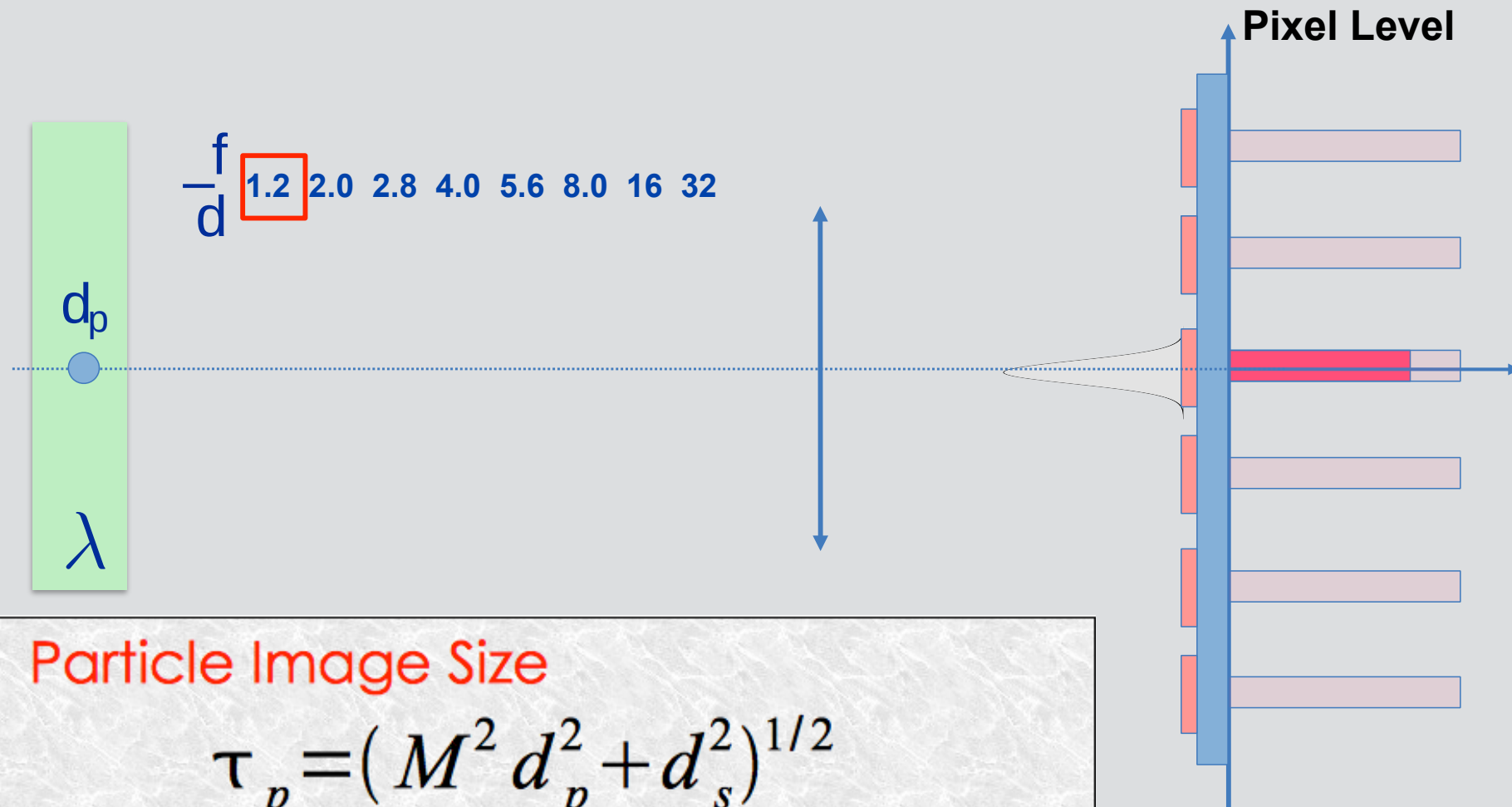


Particle Image Size

$$\tau_p = (M^2 d_p^2 + d_s^2)^{1/2}$$

$$d_s = 2.44(M + 1)\lambda \frac{f}{d} \quad \text{Diffraction spot}$$

Biais : Peak-locking : Particle image-diameter / f-stop number

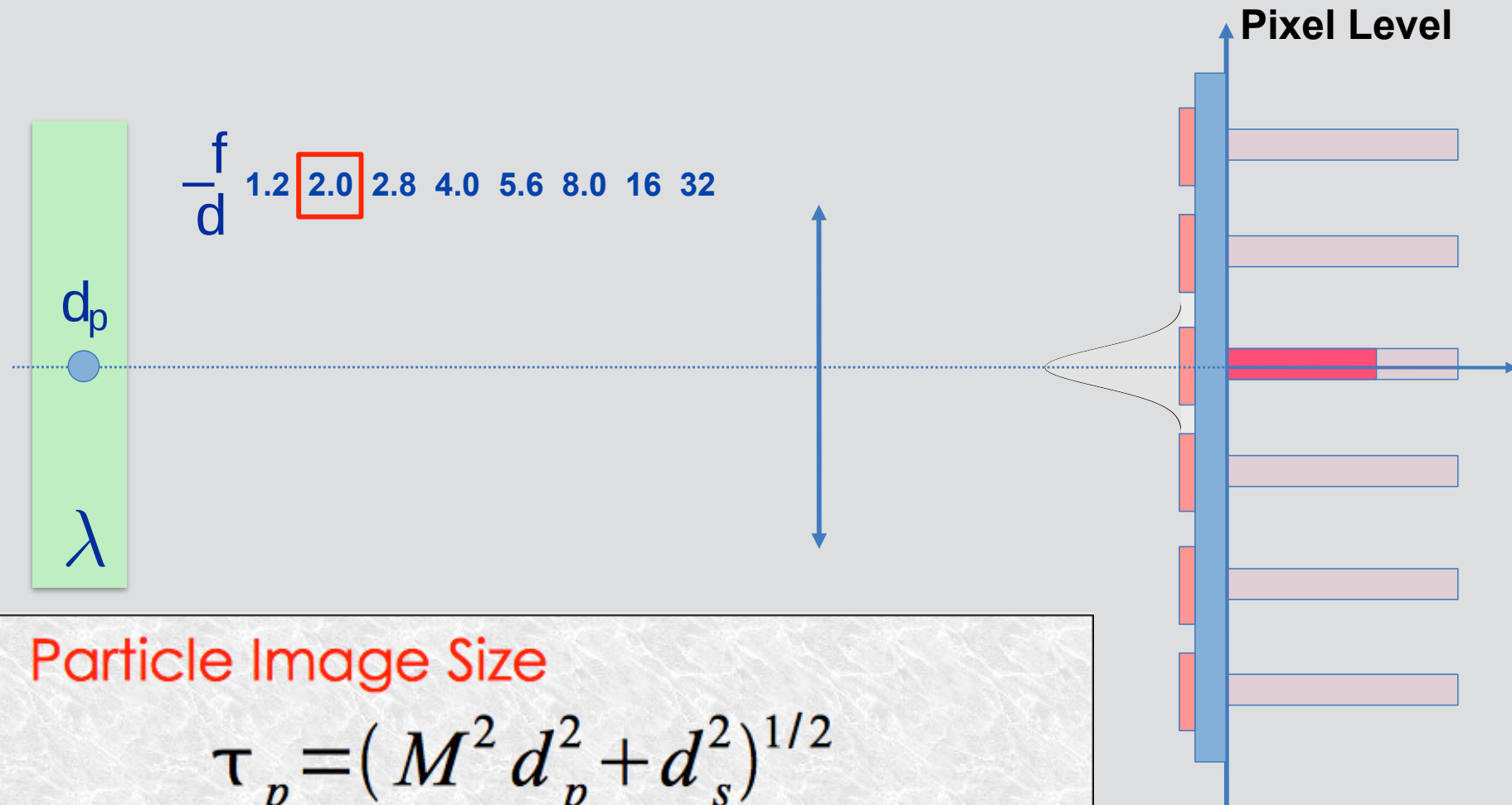


Particle Image Size

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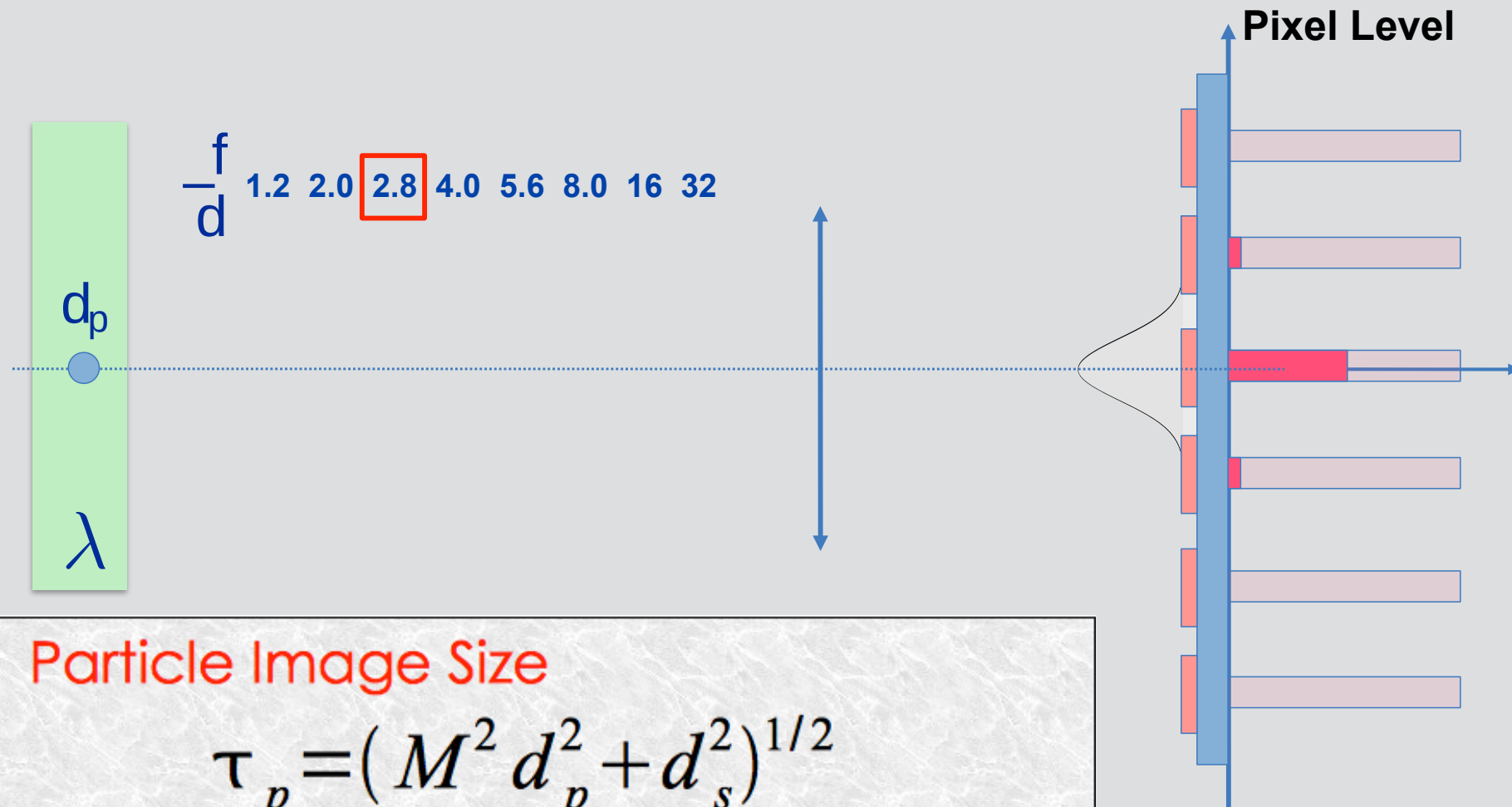


Particle Image Size

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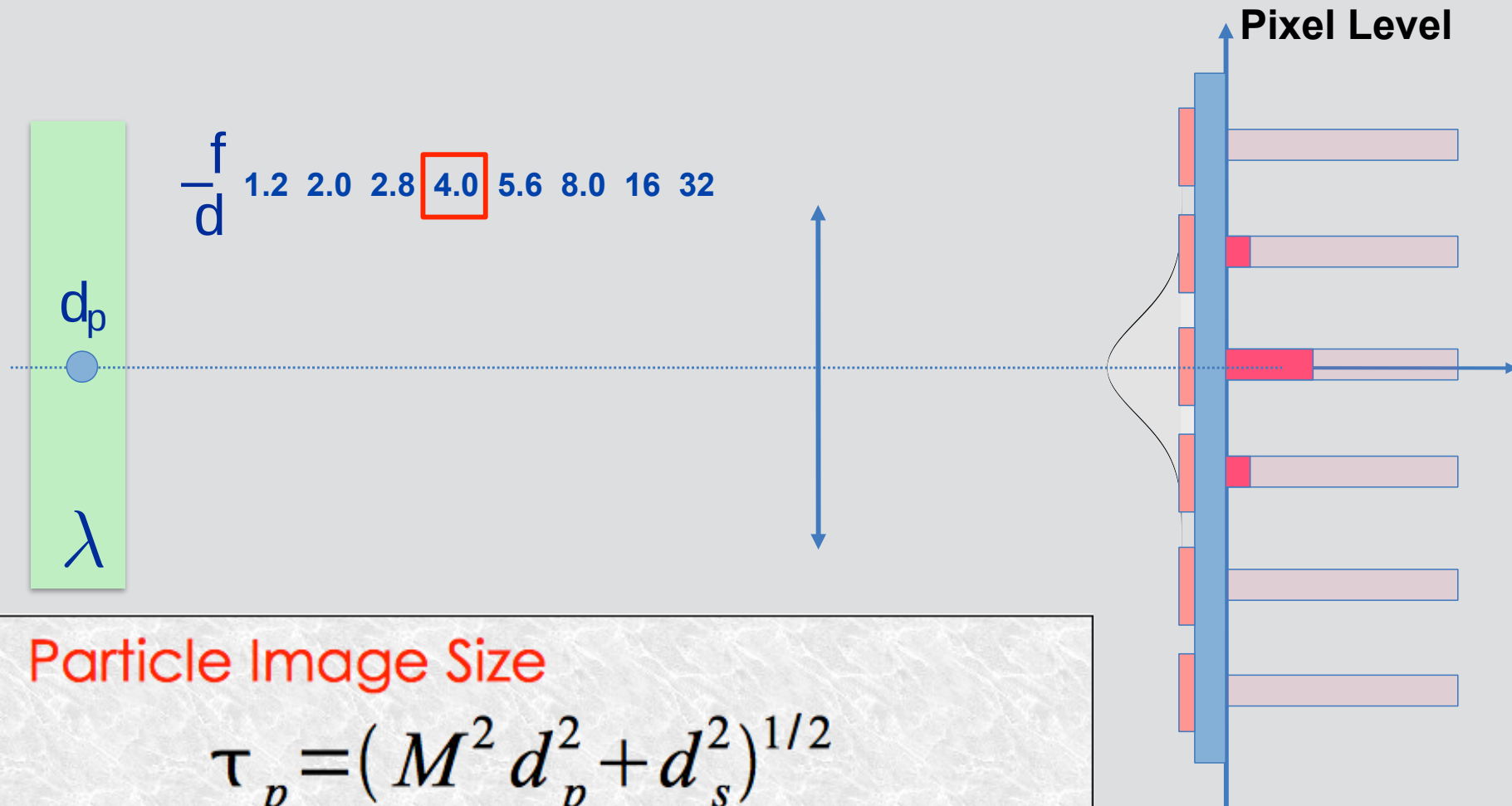


Particle Image Size

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Biais : Peak-locking : Particle image-diameter / f-stop number

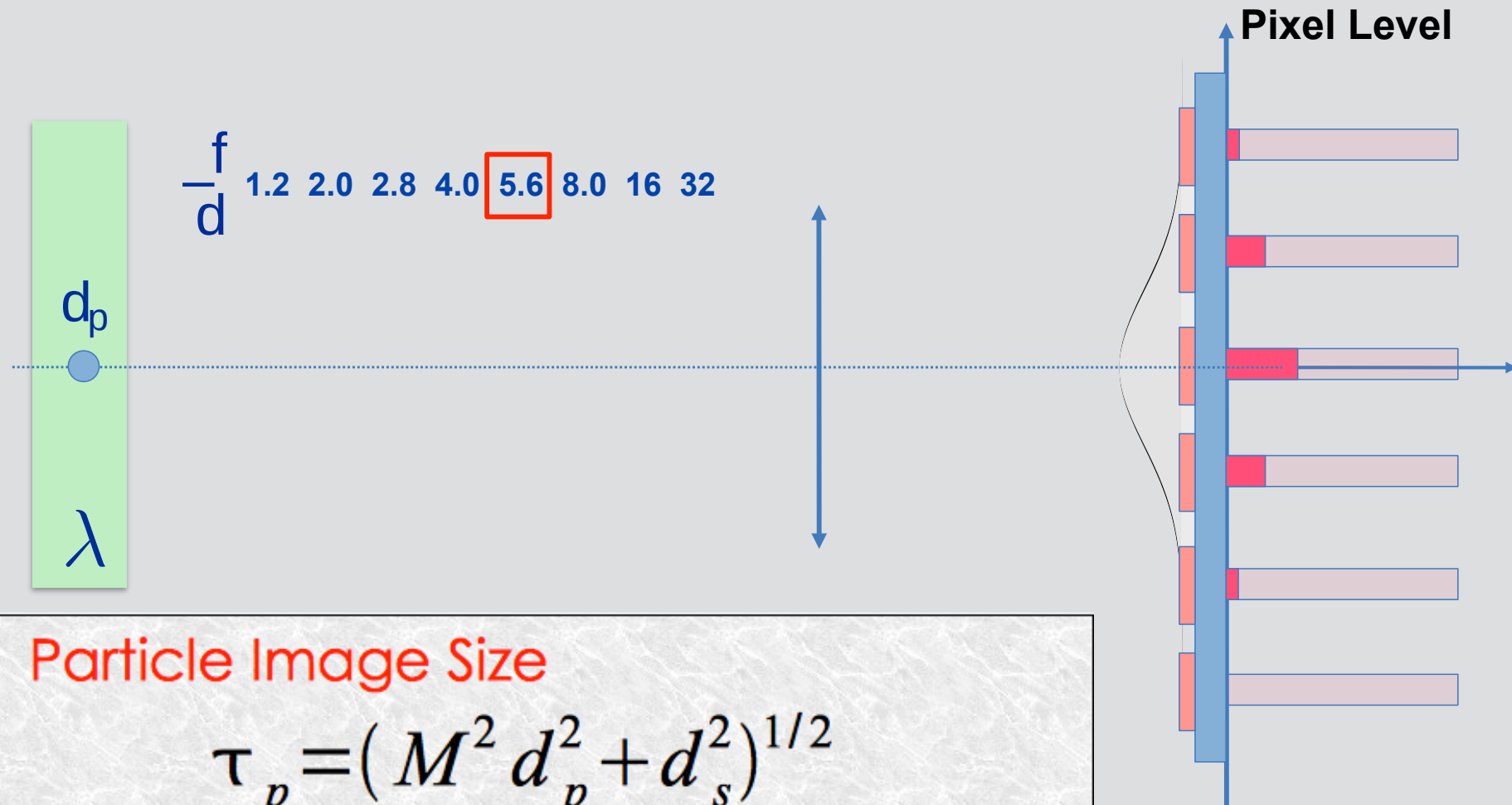


Particle Image Size

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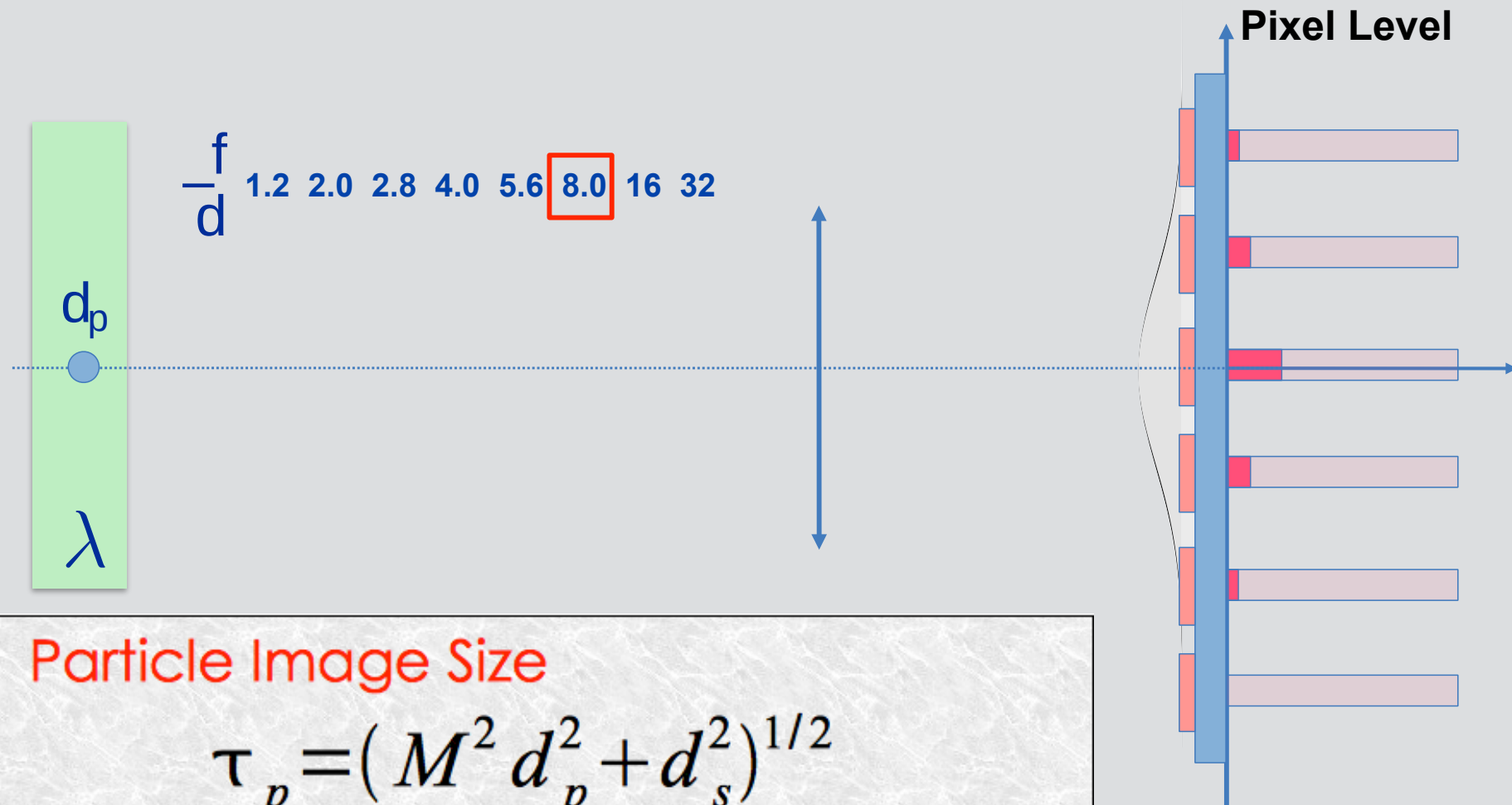


Particle Image Size

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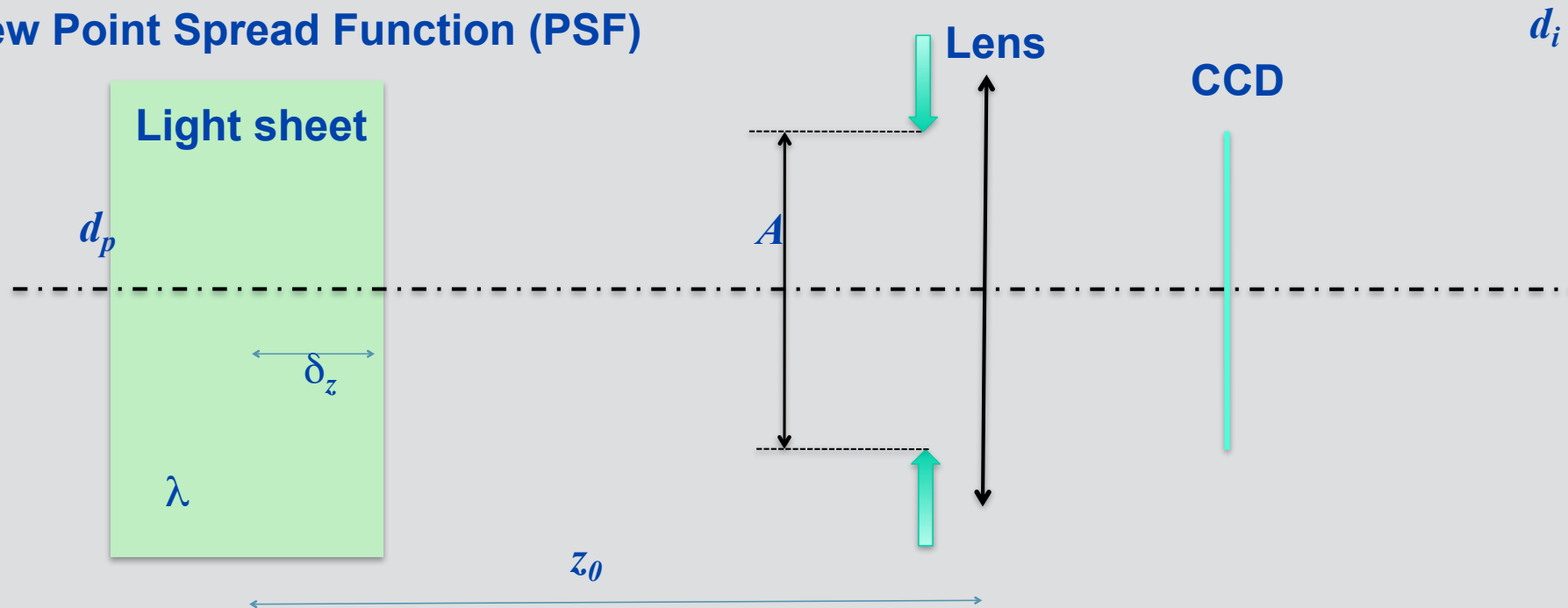
Particle Image Size

$$\tau_p = (M^2 d_p^2 + d_s^2)^{1/2}$$

$$d_s = 2.44(M + 1)\lambda \frac{f}{d} \quad \text{Diffraction spot}$$

Biais : Peak-locking : Particle image-diameter / f-stop number

New Point Spread Function (PSF)



$$d_i \cong \sqrt{d_o^2 + d_s^2 + d_f^2}$$

with :

$$d_o = M d_p$$

$$d_s = 2.44(1 + M) f^\# \lambda$$

$$d_f = \frac{M \delta_z A}{z_0 + \delta_z}$$

particle image diameter

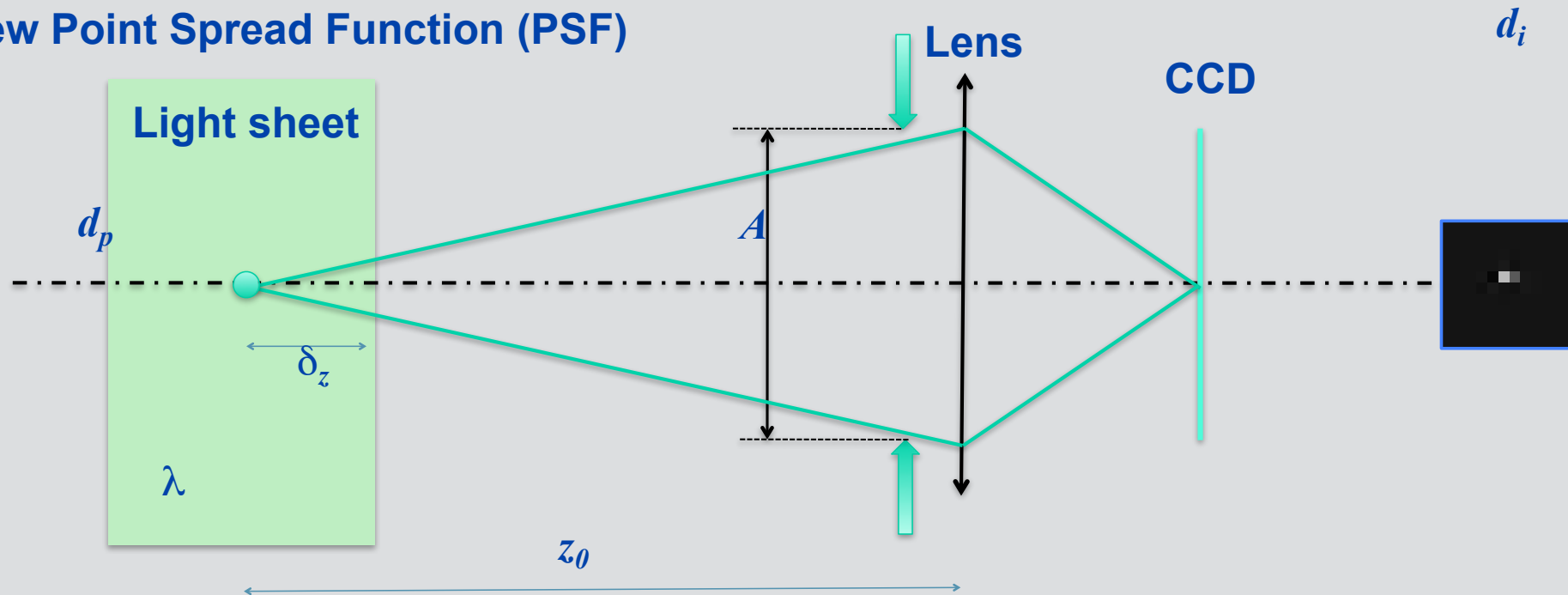
optical particle diameter

diffraction limit spot diameter

diameter of an out-of-focus particle

Biais : Peak-locking : Particle image-diameter / f-stop number

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particle image diameter

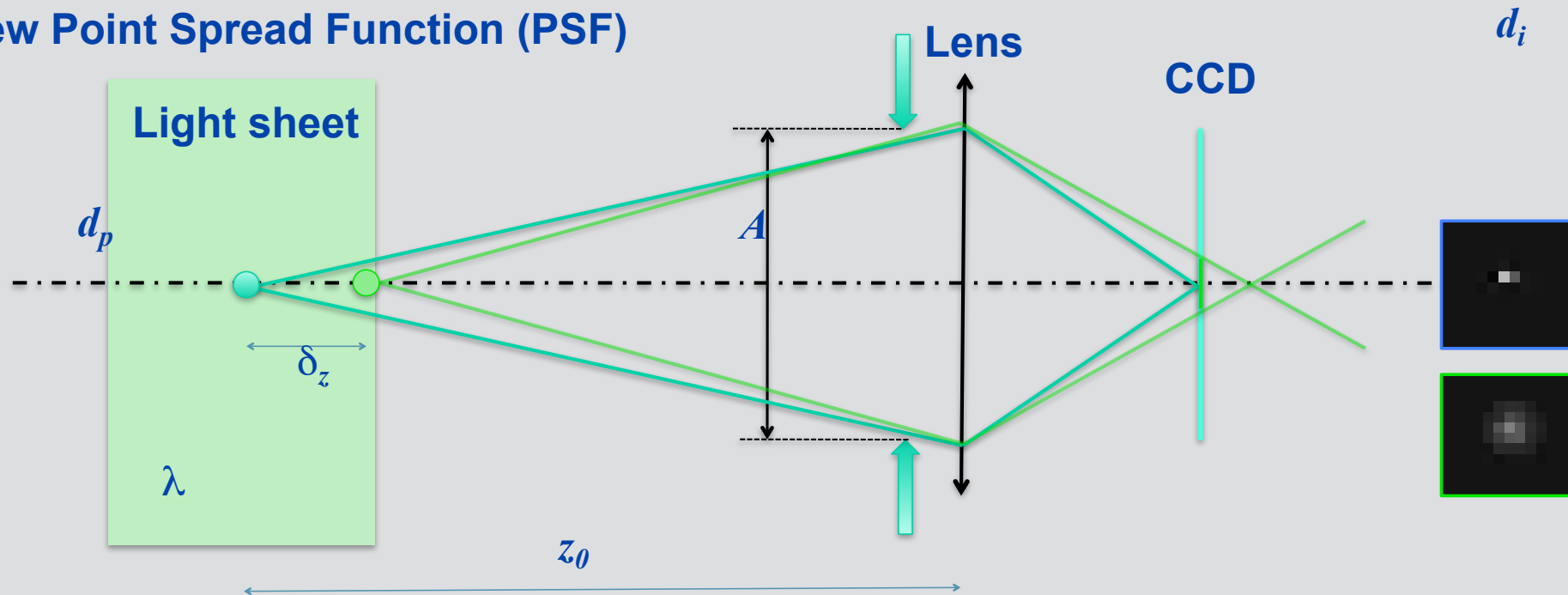
optical particle diameter

diffraction limit spot diameter

diameter of an out-of-focus particle

Biais : Peak-locking : Particle image-diameter / f-stop number

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particle image diameter

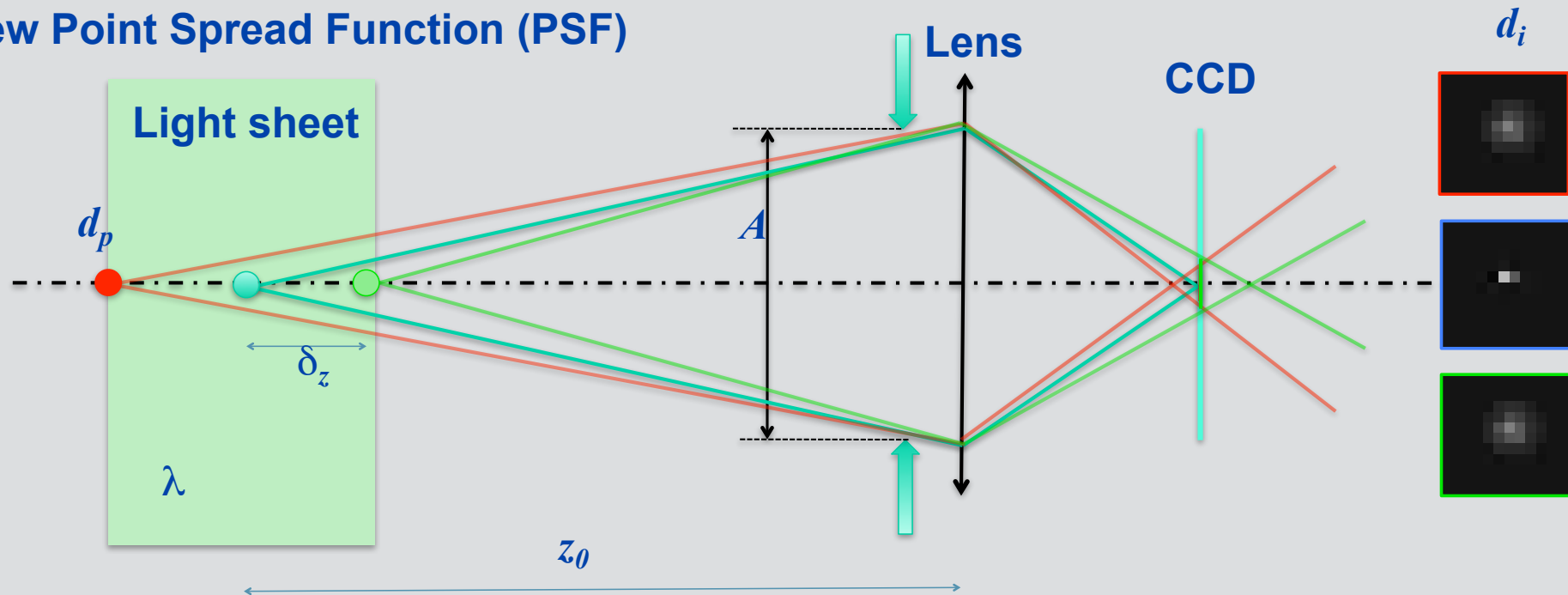
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particle image diameter

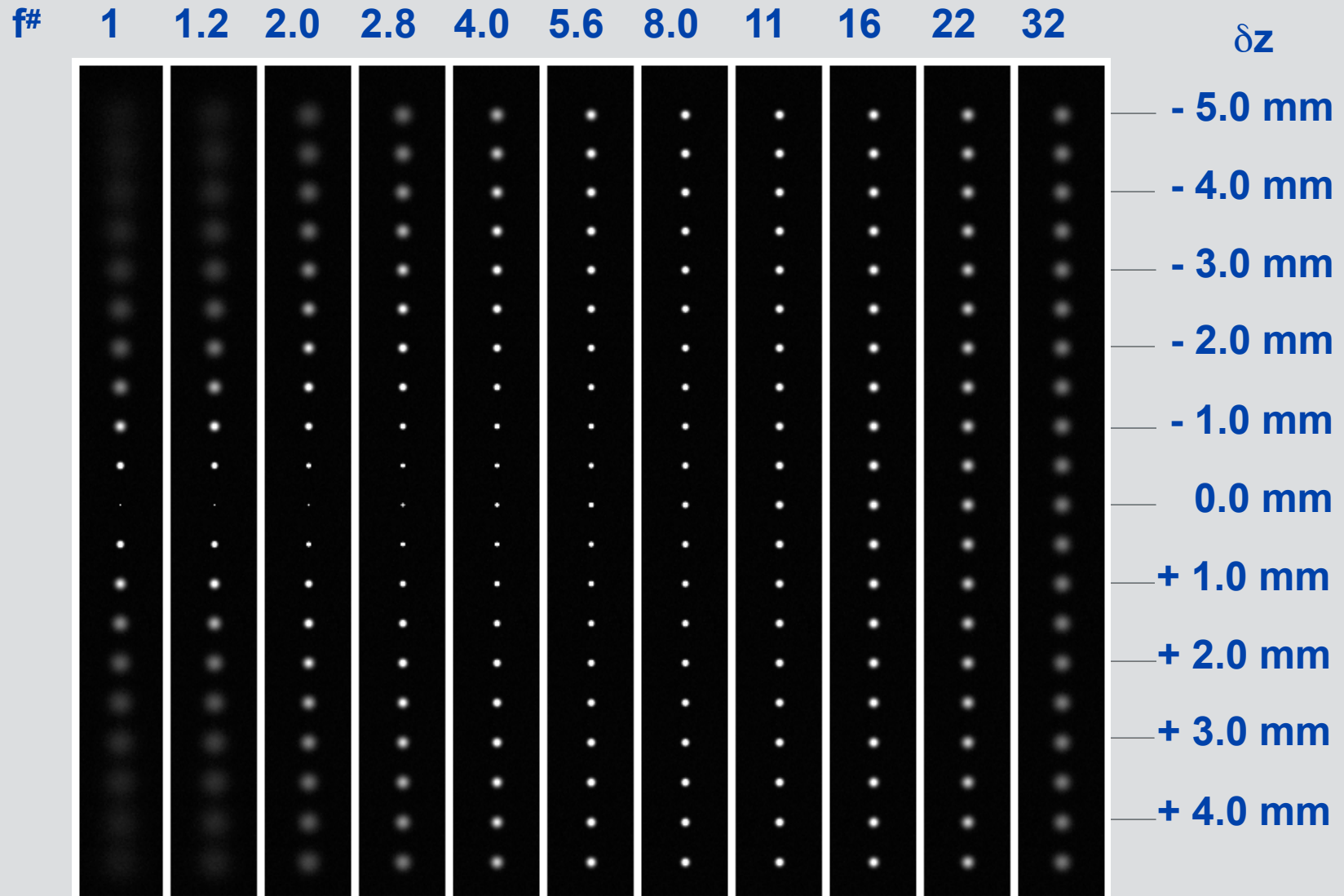
optical particle diameter

diffraction limit spot diameter

diameter of an out-of-focus particle

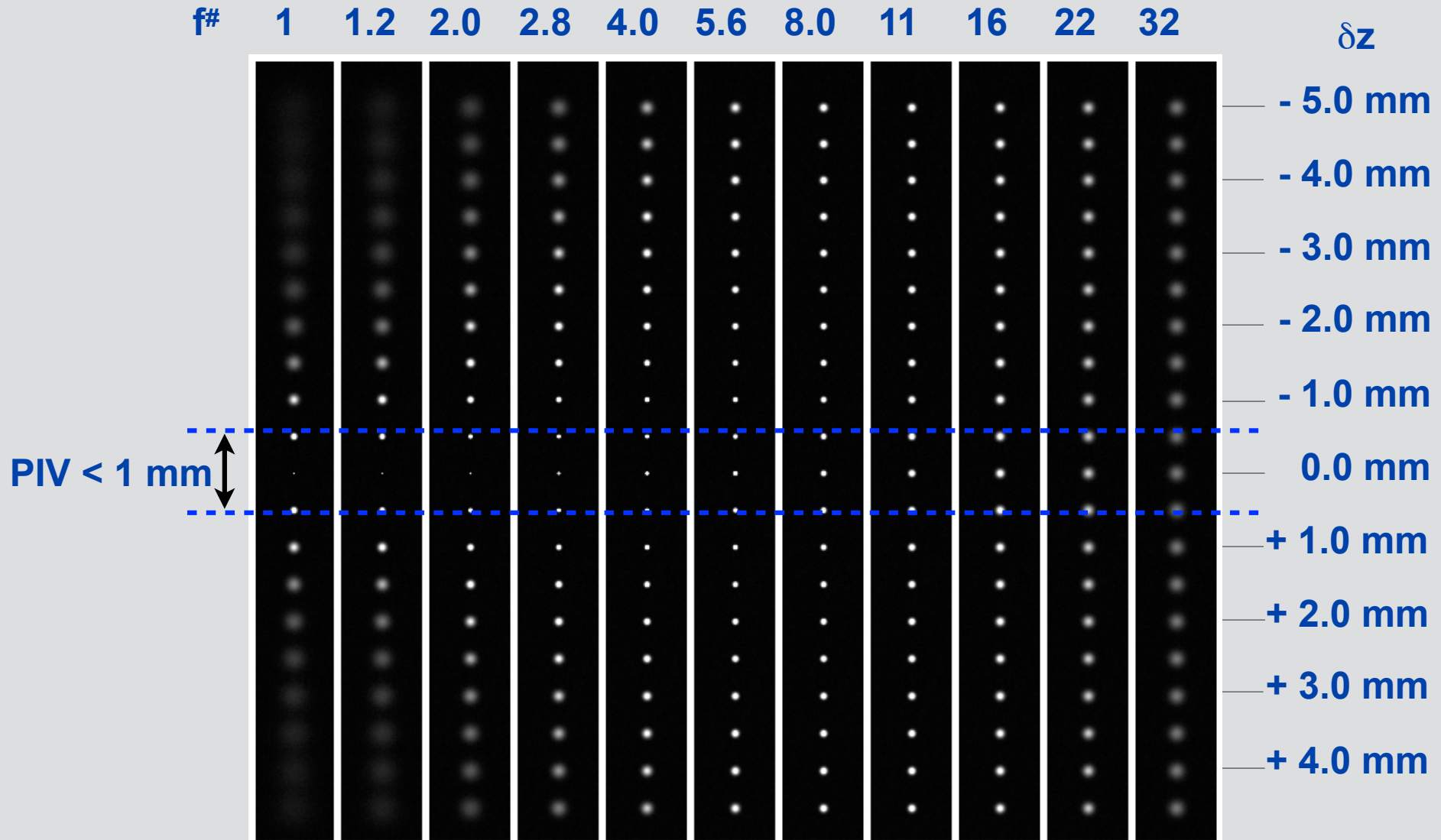
Biais : Peak-locking : Particle image-diameter / f-stop number

● Focal length 50mm, $M=0.18$, $\lambda=532\text{nm}$, $d_p=1\mu\text{m}$ (simulation)



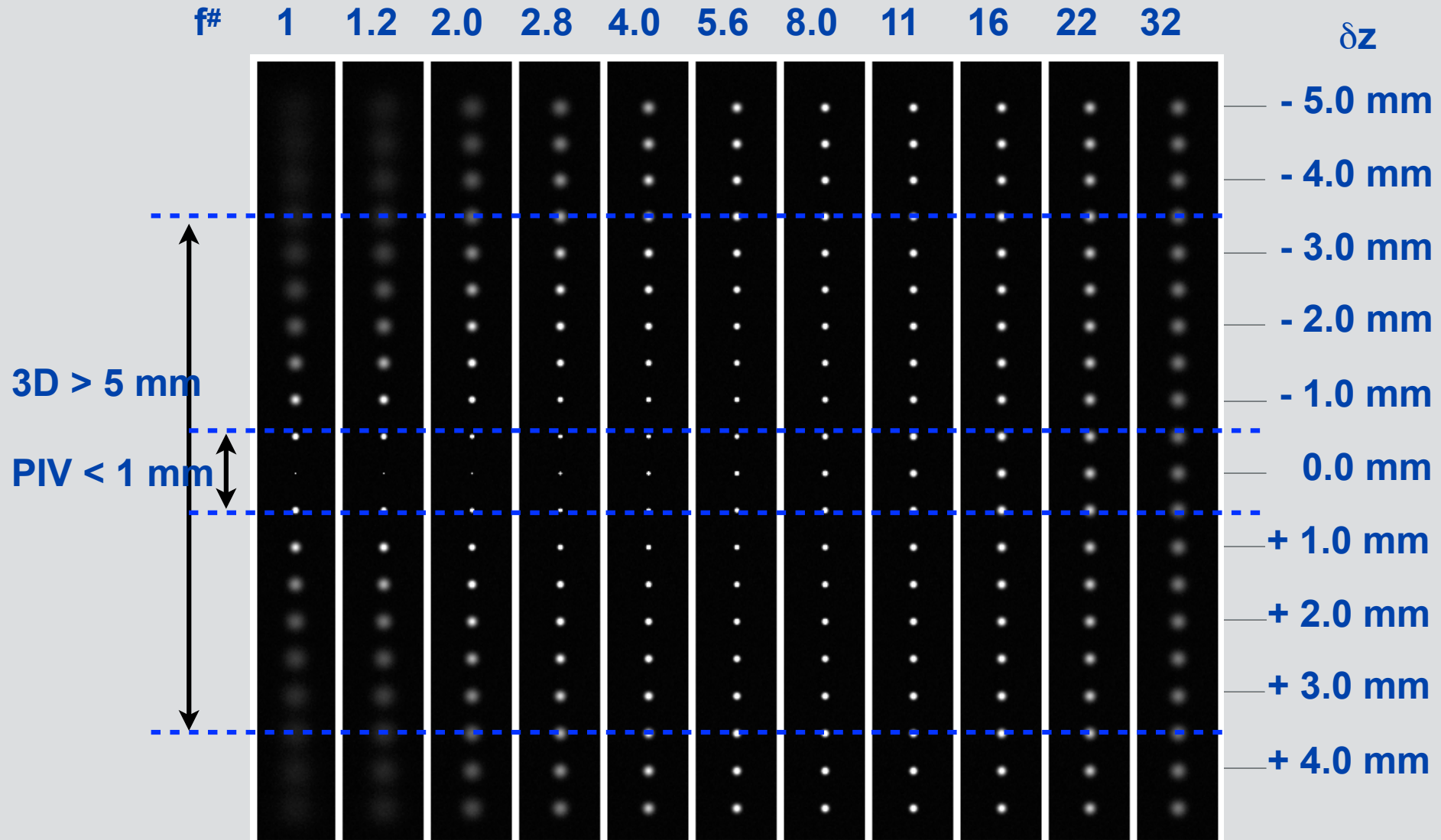
Biais : Peak-locking : Particle image-diameter / f-stop number

● Focal length 50mm, $M=0.18$, $\lambda=532\text{nm}$, $d_p=1\mu\text{m}$ (simulation)

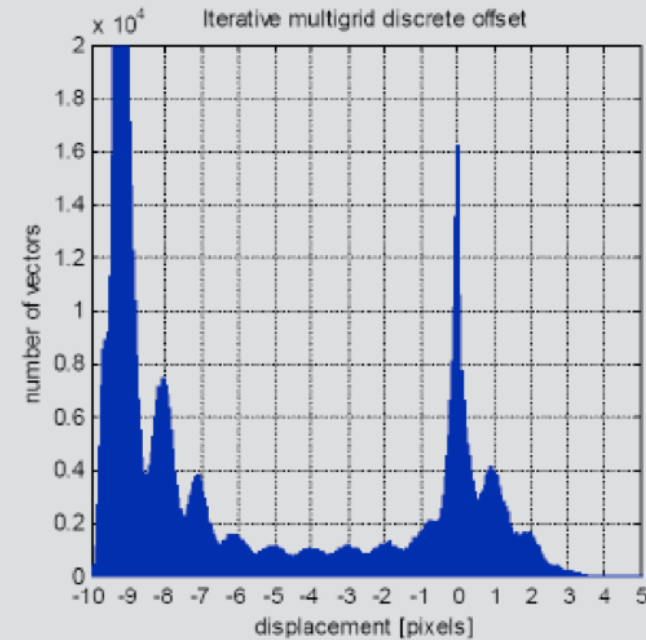
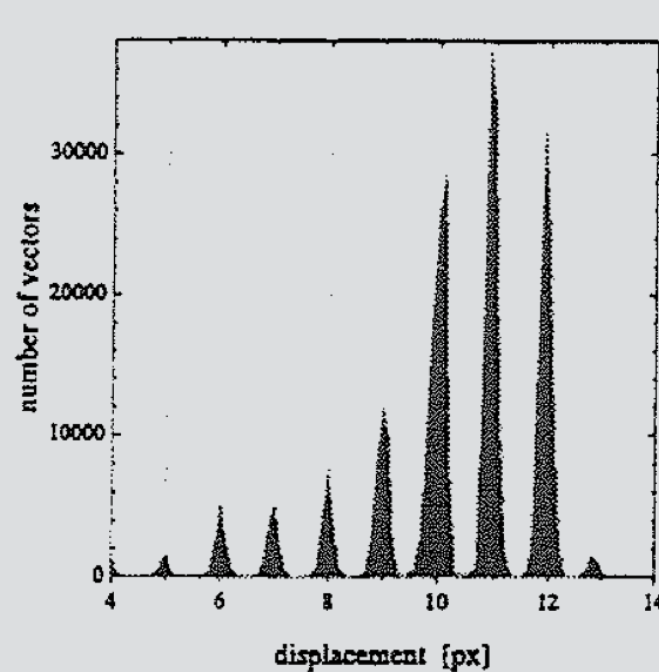


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● Focal length 50mm, $M=0.18$, $\lambda=532\text{nm}$, $d_p=1\mu\text{m}$ (simulation)

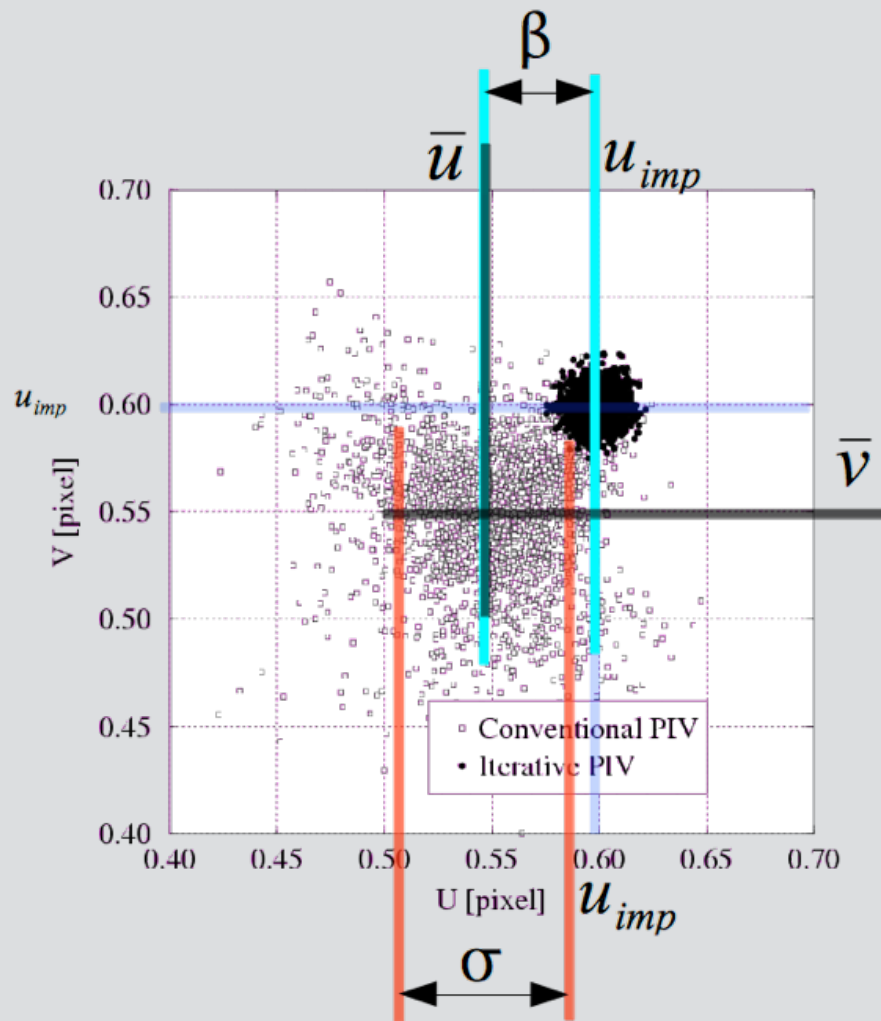


Biais : Peak-locking : Conclusions



- Toujours tracer un histogramme des vitesses (traitement PIV standard)
- Essayer de le réduire au maximum pendant la phase d'acquisition
 - Agir sur les paramètres expérimentaux (ouverture f/d de l'objectif)

Définition des erreurs



Bias Error

$$\beta = u_{imp} - \frac{1}{N} \sum_{i=1}^N u_i = u_{imp} - \bar{u}$$

Constant systematic portion of measurement error

Random Error

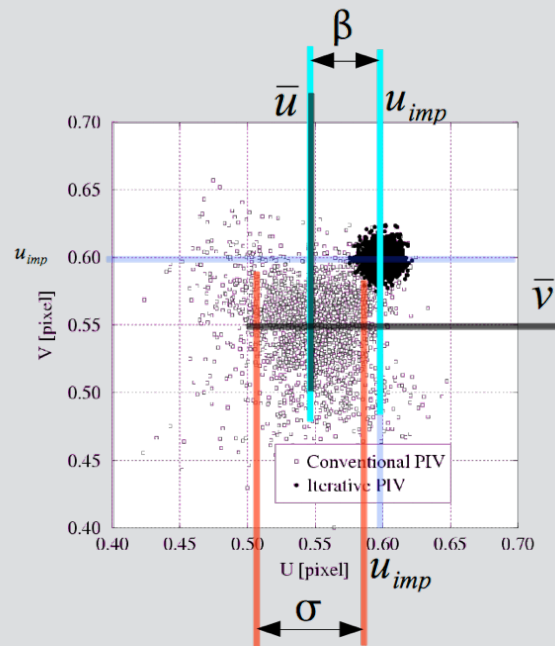
$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (u_i - \bar{u})^2}$$

Random portion of measurement error

Total Error

$$\delta = \sqrt{\frac{1}{N} \sum_{i=1}^N (u_i - u_{imp})^2} = \sqrt{\beta^2 + \sigma^2}$$

Définition des erreurs



Bias Error

$$\beta = u_{imp} - \frac{1}{N} \sum_{i=1}^N u_i = u_{imp} - \bar{u}$$

Constant systematic portion of measurement error

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Random portion of measurement error

Total Error

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● Biais systématiques

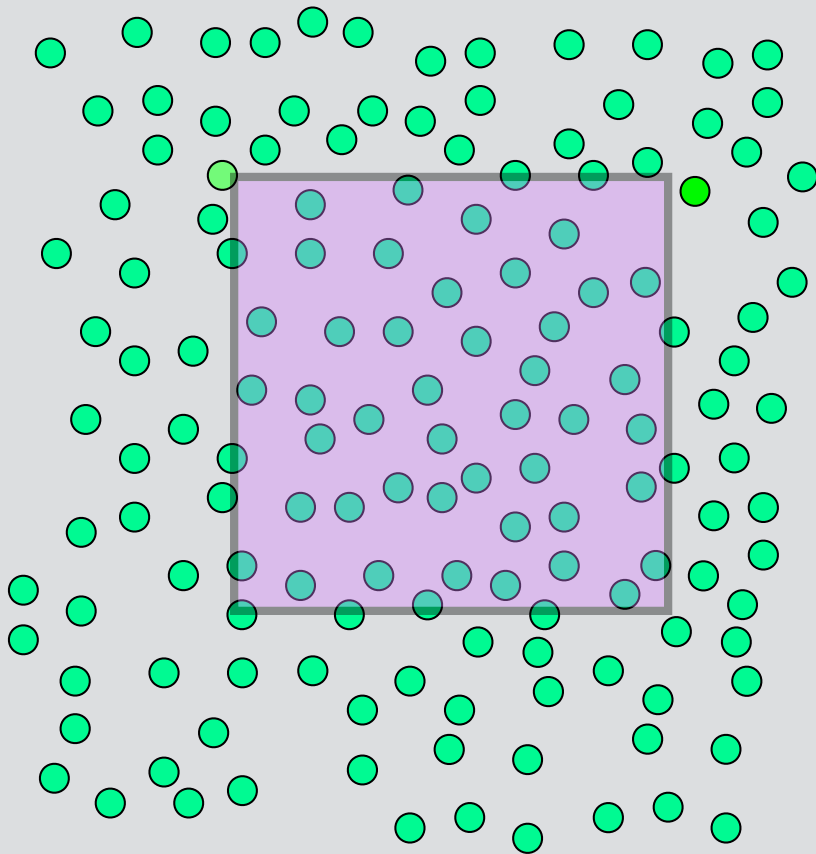
- Effet de la perspective
- Déformations optiques
- Phénomène de blocage de pic (peak-locking)

● Erreurs aléatoires

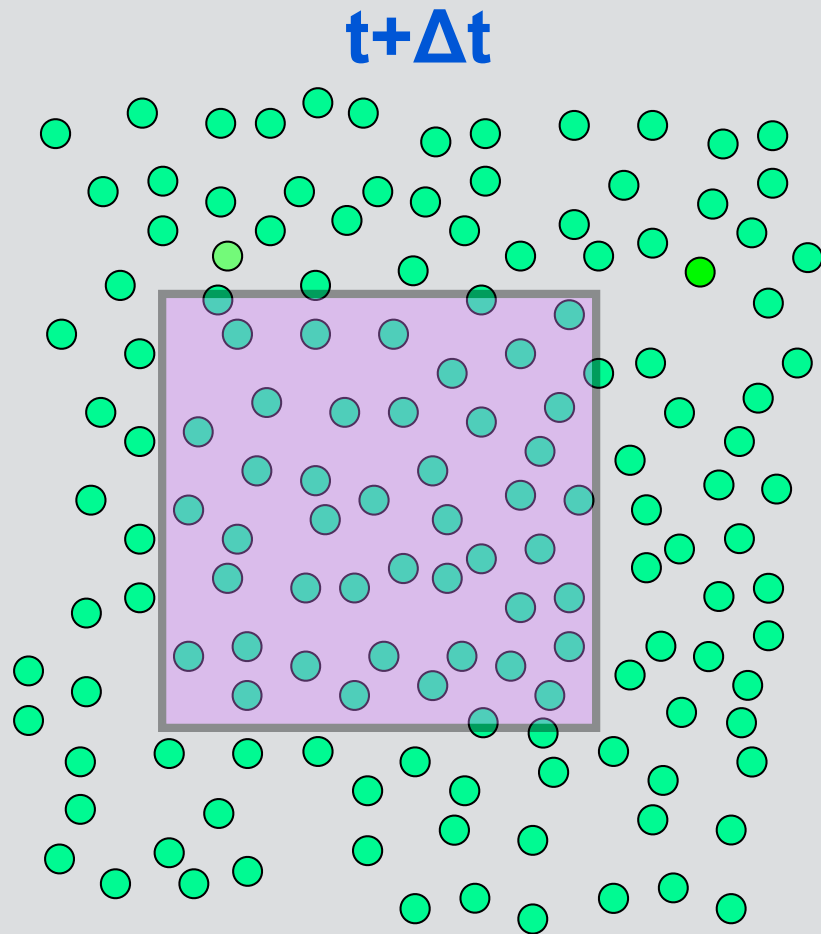
- Vitesses dans le plan (in-plane particle motion)
- Vitesses perpendiculaires au plan (out-of plane particle motion)
- ...

Déplacement des particules dans le plan (in-plane motion)

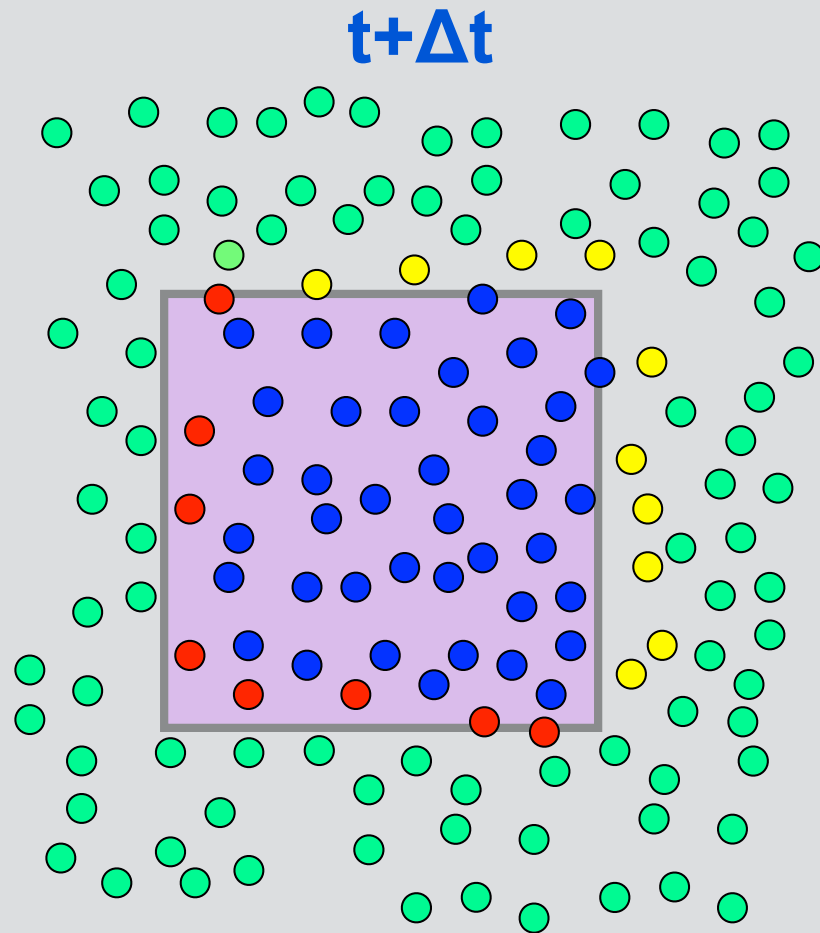
t



Déplacement des particules dans le plan (in-plane motion)

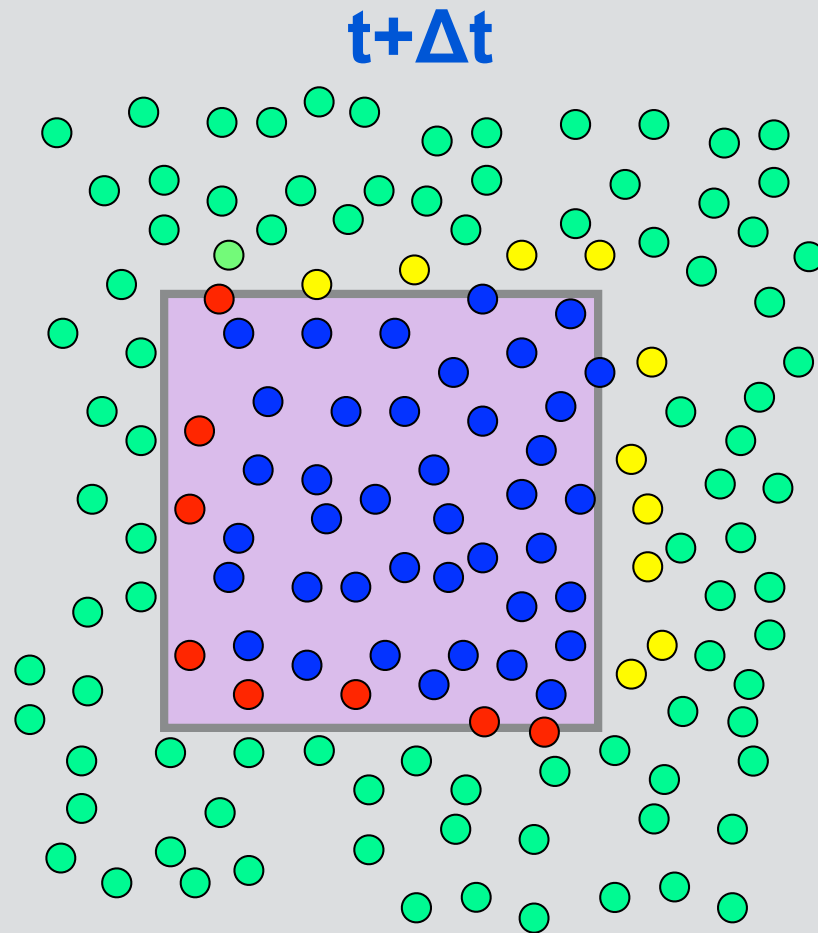


Déplacement des particules dans le plan (in-plane motion)



- Particules isolées entrantes
- Particules isolées sortantes
- Particules intervenant dans la corrélation

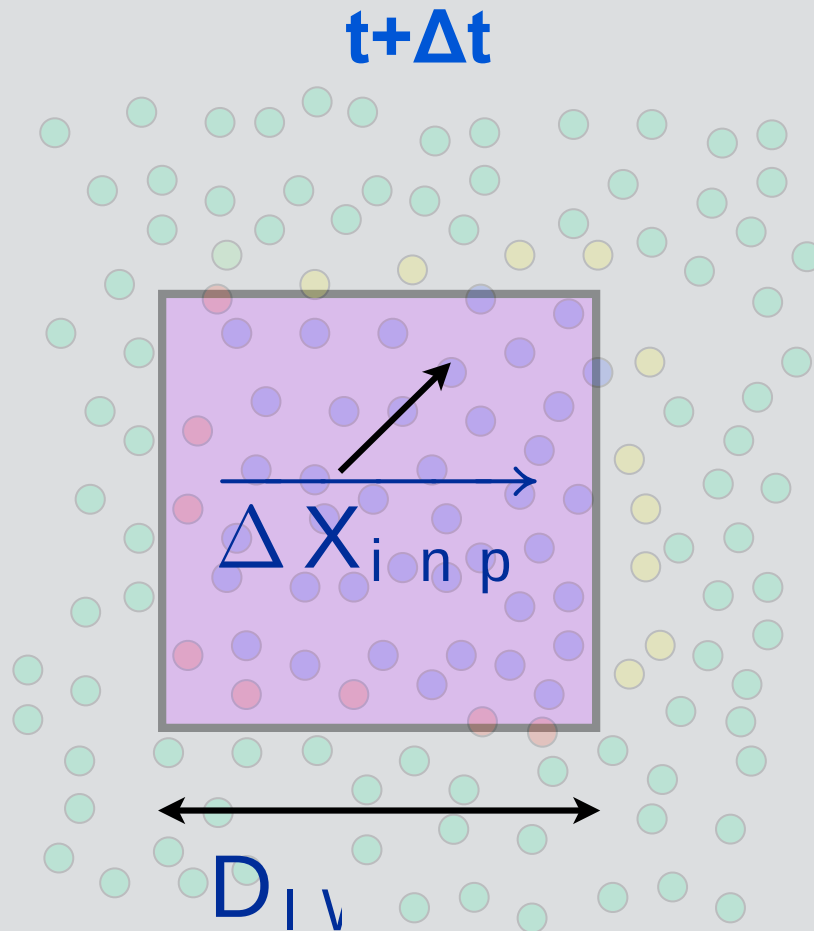
Déplacement des particules dans le plan (in-plane motion)



- Particules isolées entrantes
- Particules isolées sortantes
- Particules intervenant dans la corrélation

- Diminution du nombre de particules contribuant au pic de corrélation
- Augmentation du bruit
- Fonction de u_x et u_y

Déplacement des particules dans le plan (in-plane motion)



- Particules isolées entrantes
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- Particules intervenant dans la corrélation

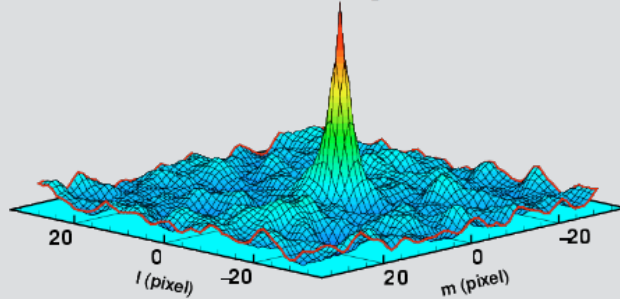
- Diminution du nombre de particules contribuant au pic de corrélation
- Augmentation du bruit
- Fonction de u_x et u_y

Critère $\left| \frac{\overrightarrow{\Delta X_{i n p}}}{D_{I W}} \right| < n \frac{1}{4}$

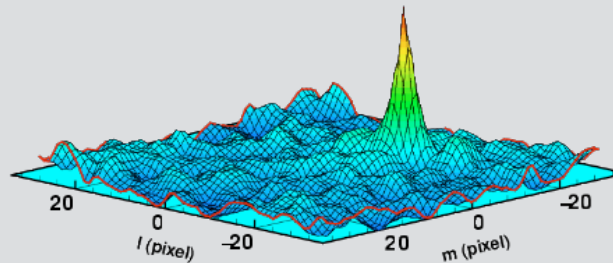
Exemples de signaux de corrélation pour 3 vitesses

Exemples de signaux de corrélation pour 3 vitesses

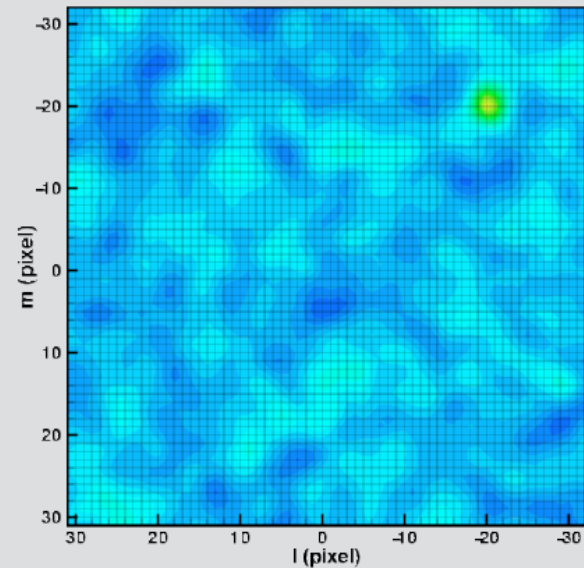
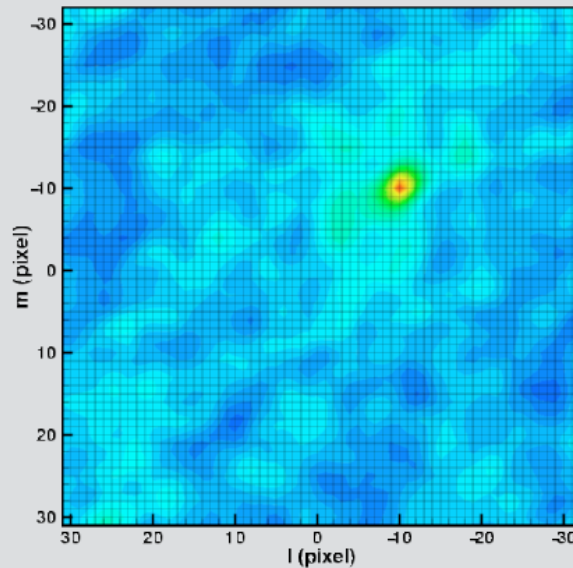
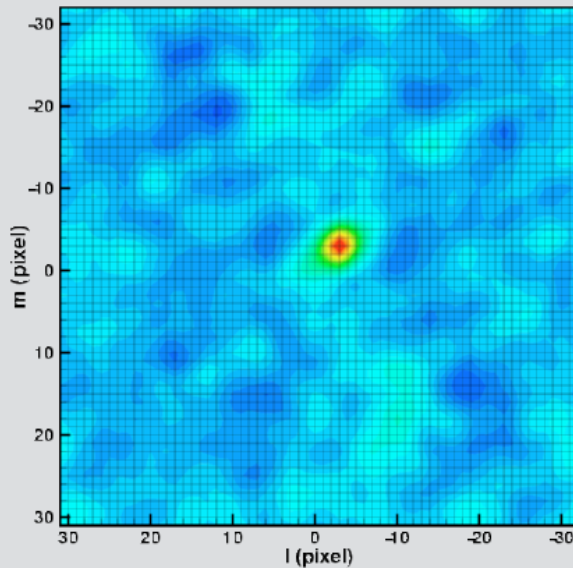
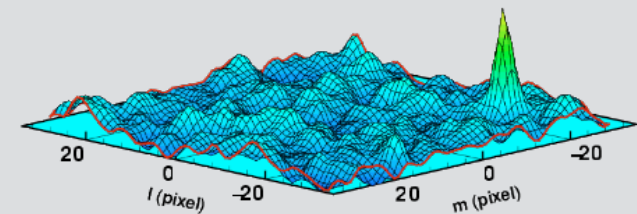
$u \sim v \sim 3$ pixels



$u \sim v \sim 10$ pixels



$u \sim v \sim 20$ pixels



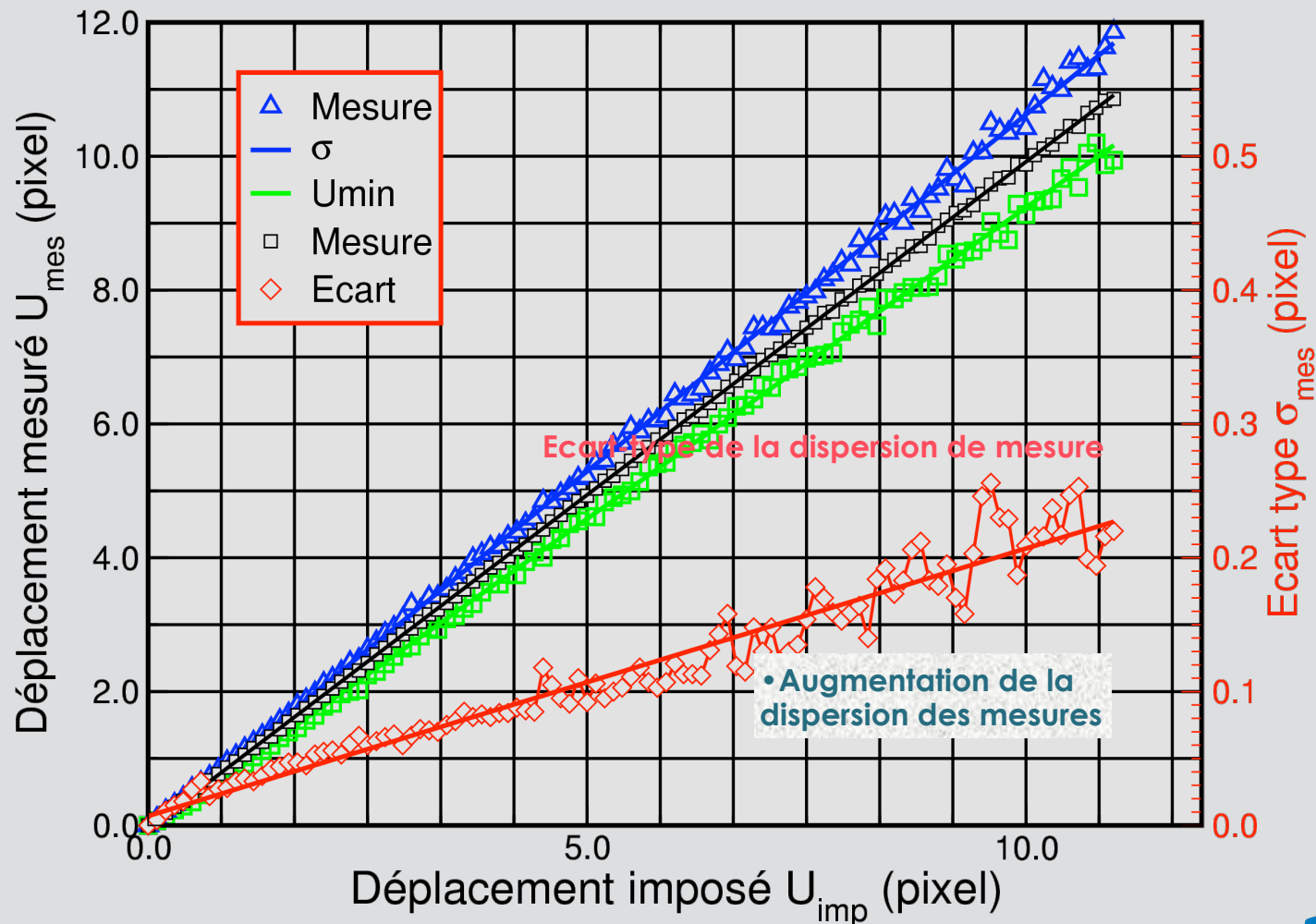
**Diminution du rapport signal/bruit
lorsque la vitesse augmente**

Evolution de l'erreur aléatoire en fonction du bruit

Random Error

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (u_i - \bar{u})^2}$$

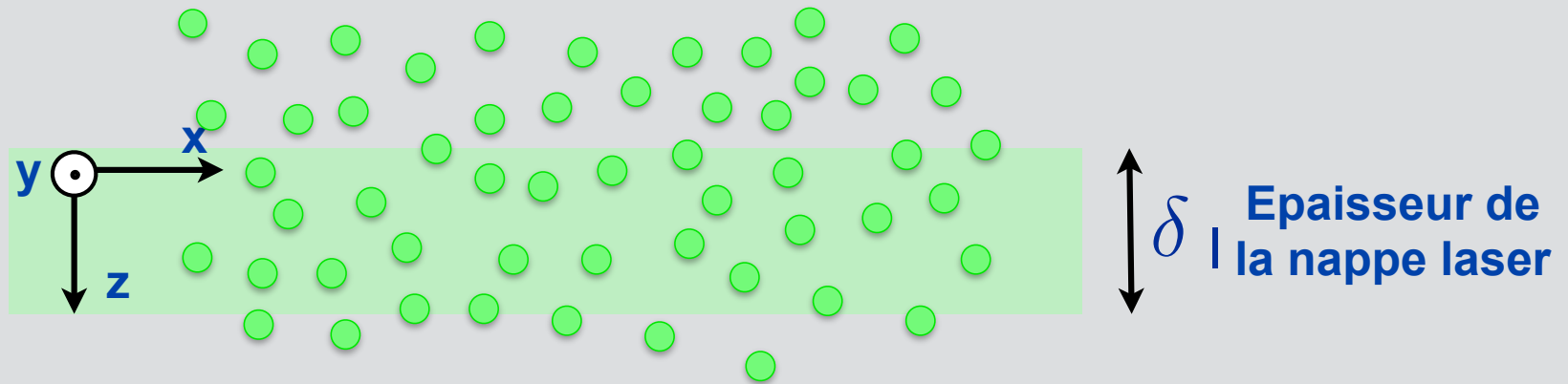
Random portion of measurement error



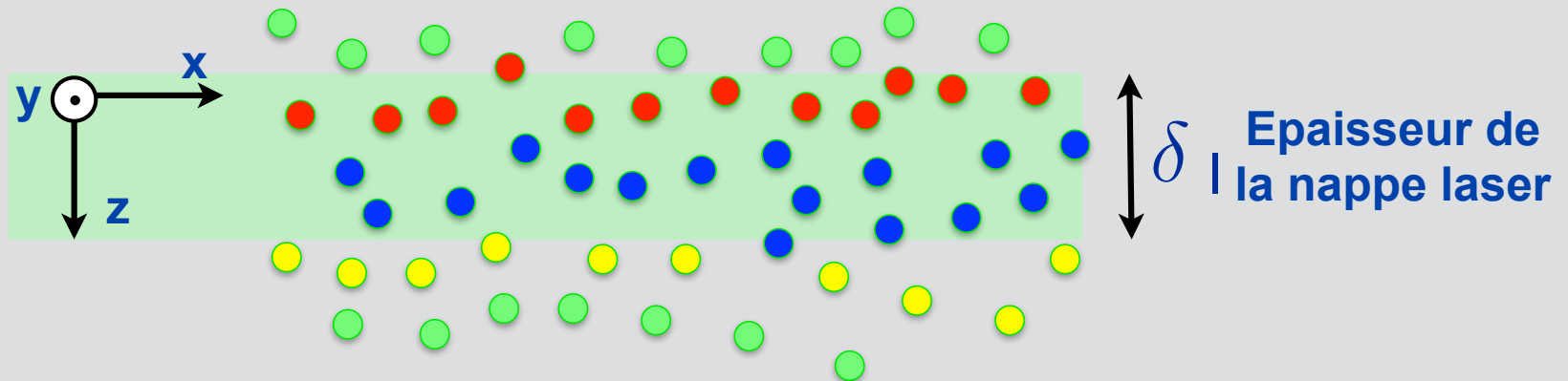
Déplacement des particules perpendiculairement au plan



Déplacement des particules perpendiculairement au plan

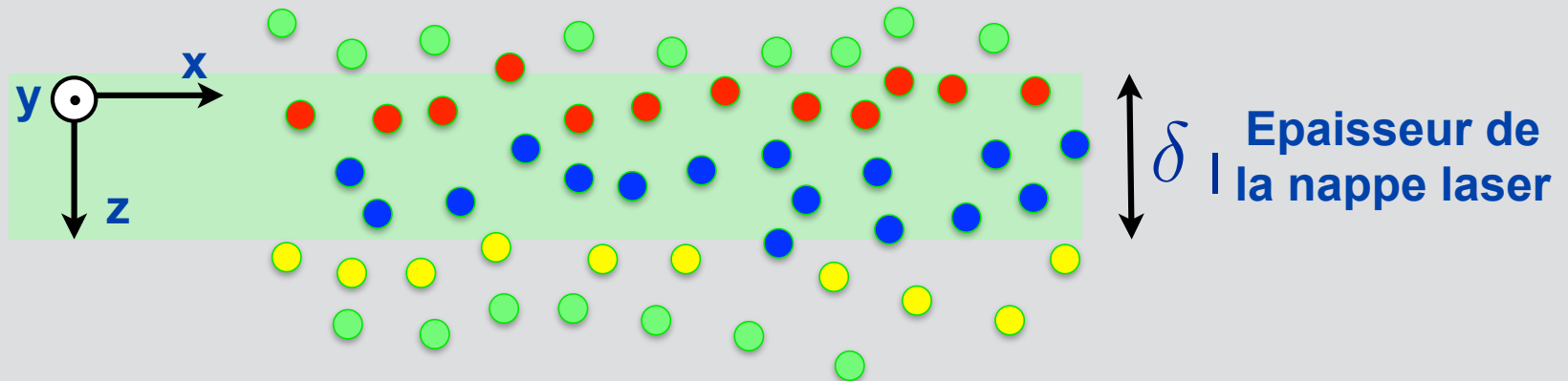


Déplacement des particules perpendiculairement au plan



- Particules isolées entrantes
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Déplacement des particules perpendiculairement au plan

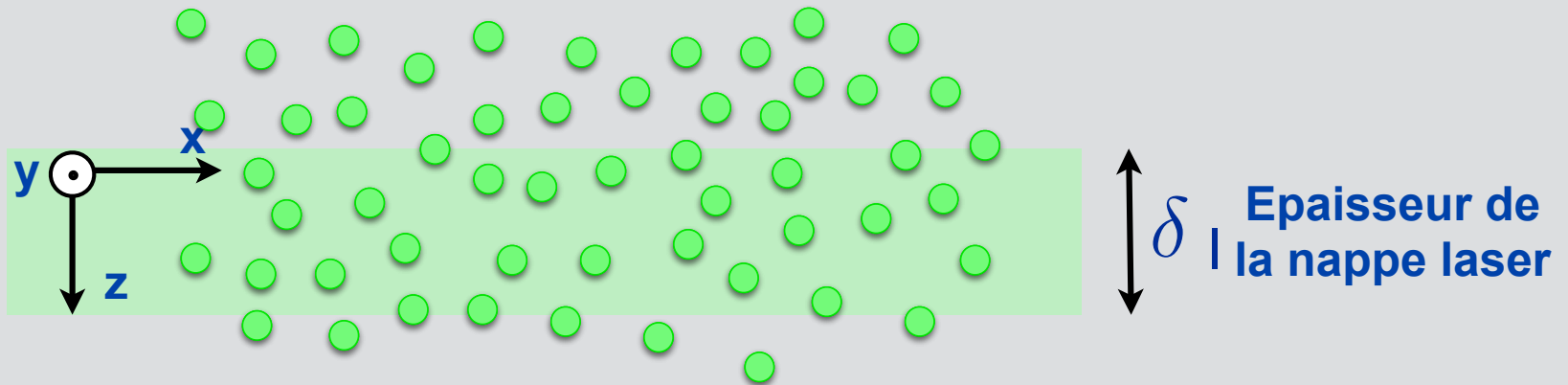


- Particules isolées entrantes
- Particules isolées sortantes
- Particules intervenant dans la corrélation

Déplacement en z $\Delta_z = u_z \Delta_t$

Critère $\left| \frac{\Delta_z}{\delta_l} \right| < \frac{1}{4}$

Déplacement des particules perpendiculairement au plan

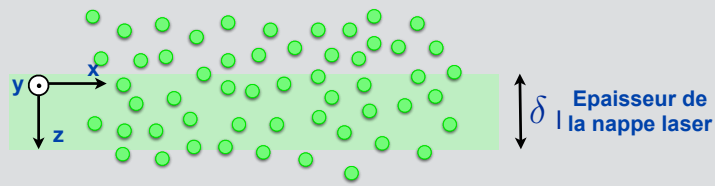


- Particules isolées entrantes
- Particules isolées sortantes
- Particules intervenant dans la corrélation

Déplacement en z $\Delta_z = u_z \Delta_t$

Critère $\frac{\Delta_z}{\delta_l} < \frac{1}{4}$

Déplacement des particules perpendiculairement au plan



- Particules isolées entrantes
- Particules isolées sortantes
- Particules intervenant dans la corrélation

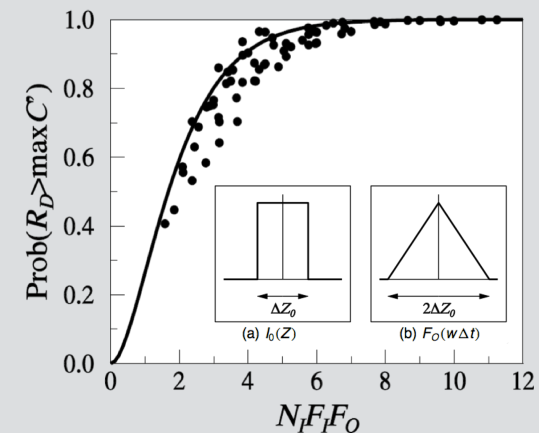
Déplacement en z $\Delta_z = u_z \Delta_t$

Critère $\frac{\Delta_z}{\delta_l} < \frac{1}{4}$

- Pour réduire les effets 3D, il faut diminuer le temps entre les images ($\Delta z \sim \frac{1}{4}$ nappe) et par conséquent réduire la gamme de déplacement
 - diminution des déplacements dans le plan
 - Avoir une précision de mesure élevée pour conserver une dynamique suffisante dans une gamme de faible déplacement
- Augmenter l'épaisseur de la nappe laser
- Décaler les nappes laser si la composante u_z est pratiquement uniforme et homogène dans le plan de mesure (soufflerie...)

Règles de base pour la PIV par corrélation

- L'étape d'acquisition est essentielle
 - Ensemencement homogène et adapté
 - Densité
 - Réduire le fond dans l'image
 - Intervalle de temps entre les images
 - Nappe laser d'intensité homogène
 - Minimiser le blocage de pic (histogramme)
 -



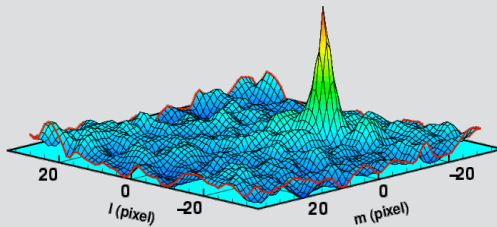
- Quel que soit l'algorithme, une « faible qualité d'image » conduira toujours à l'augmentation des bruits de mesure et à la diminution de sa précision

Règles de base pour la PIV par corrélation

L'étape d'acquisition est essentielle

- Ensemencement homogène et adapté
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- Minimiser le blocage de pic
-

Quel que soit l'algorithme, une « faible qualité d'image » conduira toujours à l'augmentation des bruits de mesure et à la diminution de sa précision



N_I : Nombre de particule dans IW

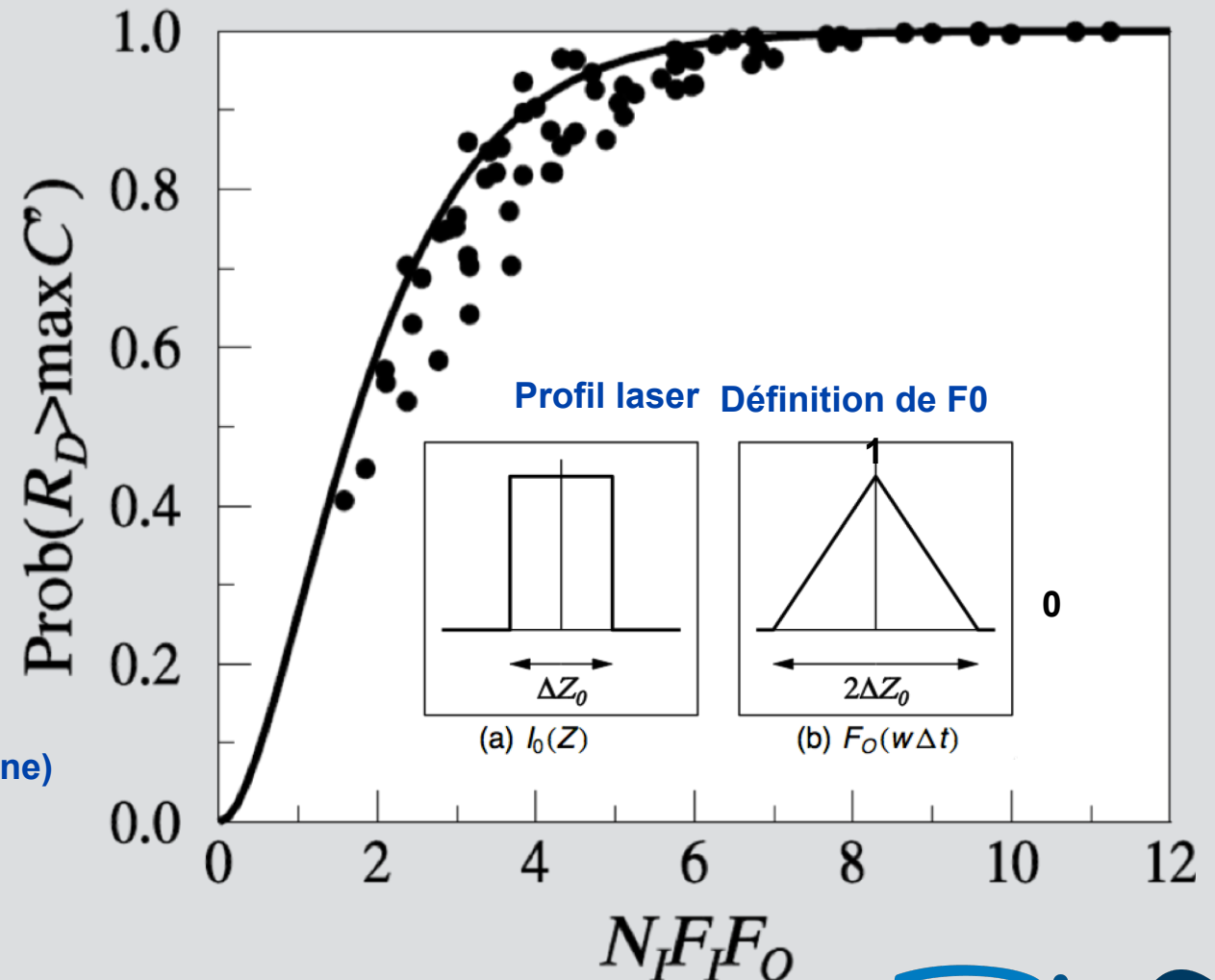
F_I : Pondération perte particule (in-plane)

1 pas de perte - 0 : 100% de perte

F_O : Pondération perte particule (out-of plane)

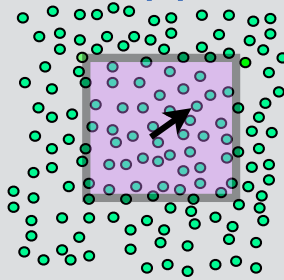
1 pas de perte - 0 : 100% de perte

Probabilité que le niveau du pic de corrélation soit supérieur au bruit dans l'espace de corrélation en fonction du nombre effectif de particule contribuant à la corrélation $N_I F_I F_O$ [Keane et Adrian (2002)]



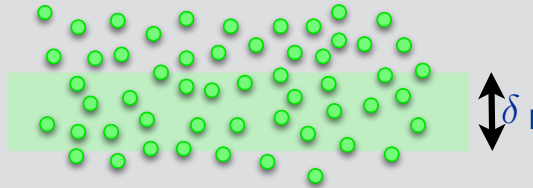
Règles de base pour la PIV par corrélation

- Déplacement des particules dans le plan de la nappe laser



$$\left| \frac{\overrightarrow{\Delta X_{i \text{ n p}}}}{D_{l w}} \right| < \frac{1}{4}$$

- Déplacement des particules perpendiculairement à la nappe laser



$$\left| \frac{\overrightarrow{\Delta}}{\delta} \right| < -$$

- Gradient de vitesse dans la maille d'analyse

- Moins de 8 pixels de variation pour une maille de 32x32

$$\left| \frac{\partial}{\partial} (\overrightarrow{\Delta}) \right| < -$$

- Concentration en particule

$$N_i \geq 1$$