BMEGEÁTMW03 „FLOW MEASUREMENTS”

Optical flow visualization, Introduction to lasers applied to optical flow diagnostics Laser-optical measurement techniques for flow characterization

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AIM:
- VISUALIZATION of the FLOW FIELD
- MEASUREMENT of FLOW VELOCITY $\underline{v}(\underline{r},t)$

& CHARACTERISATION of PARTICULATE PHASE (d_p)

Contents:
- Lasers, examples (FlowVis, LDV, PDA, PIV, PTV(S))
- Characterization of particle-laden mixtures
- Particle dynamics, equation of motion
- Particles: seeding/tracer problematic

- Advantage / disadvantage / limits of laser-optical techniques

…lasers…
(L.A.S.E.R.)

OPERATION

continuous lasers

solid

Diode
Rod
Disk
Fiber

gas

Industrial operation:
-„sealed" up to 400W
-„turbo" up to 20kW

pulsed lasers

solid

rod
disk
fiber

gas

Industrial operation:
CO_2 & Eximer lasers

for LASER OPTICAL FLOW MEASUREMENTS:
from ~10 mW…… to ~6W

FLOW MEAS?

-Flow visualization
-LDV: Laser Doppler Velocimetry
-PDA: Phase Doppler Anemometry

Example:
diode, HeNe, Ar-Ion, Nd:YAG

FLOW MEAS?

-Flow visualization (!cont.mode)
-PIV: Particle Imaging Velocimetry
PIV, PTV(S)

Example:
Nd:YAG, CVL (copper-vapour), Ar-Ion, CO_2

main „Laser DANGER” signs

EU sign: Class 1, 1M, 2, 2M, 3R, 3B, 4
USA sign: Class I., II., III., IV.)

MEANING of the class signs:

1. : ~ equivalent to sunlight
1M. : ~ avoid to examine the light source with optical elements
2. : 400-700nm, max.1mW, cont., up to MPE=0.25s (max permissible exposition time), light protectors are not needed up to this MPE
3A,R : up to max. 5mW, cont. operation
3B : ! eye protector, safety measures: starting key and beam shutter is a must
4. : ! as all above + direct & undirect reflected lights are also dangerous

Available lasers at the Department or R&D partners:

1) for FLOW VIS:
- laser diodes (10, 25, 50, 100, 500 mW) for flow visualization (610nm, 532nm)

2) Laser Doppler Velocimeters:

2.1 15mW LDV, „ILA” LDV, HeNe: λ=632nm (red), 1D, without Bragg cell (=unshifted)

2.2 300mW LDV Melles Griot, Ar-Ion, λ=514nm, 488nm (green, blue), 2D, with Bragg cell

Others, used in R&D cooperation with other institutions:

a) LDV Laser Doppler Velocimeter:

UNI MAGDEBURG 100mW diode „POLYTEC LDV-380” l=810nm (infrared)

VKI (many, mainly 50-300mW 1D 632nm (red) or 2D

b) Particle Image Velocimeter and **Particle Tracking Velocimetry & Sizing**

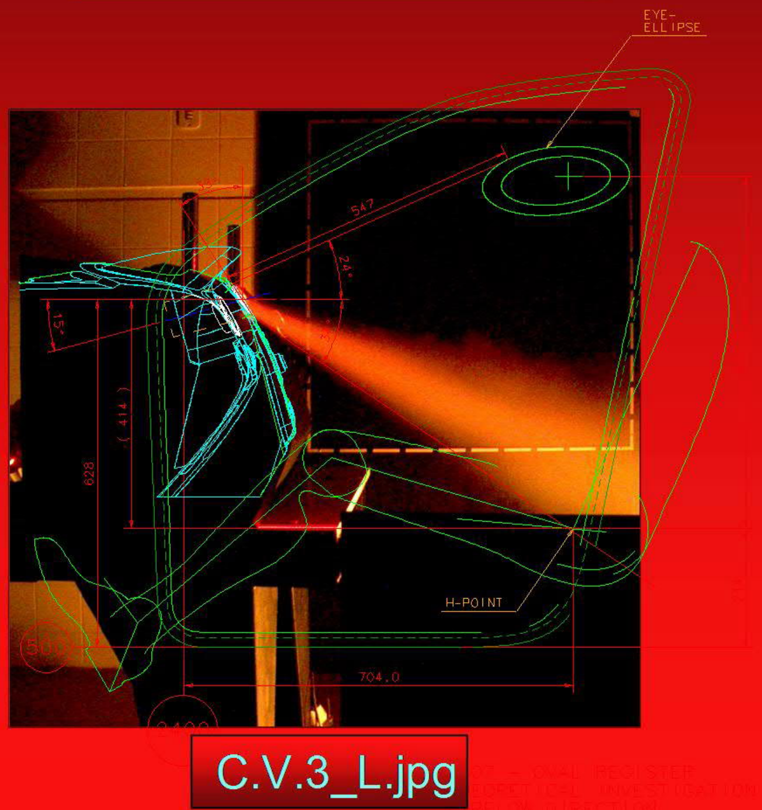
PIV+PTV(S): VKI: Von Kármán Institute (Nd:YAG, 6W, green)

Other PIV-s: from UNI Magdeburg; ELTE – PIV Lab for Atmospheric Flows

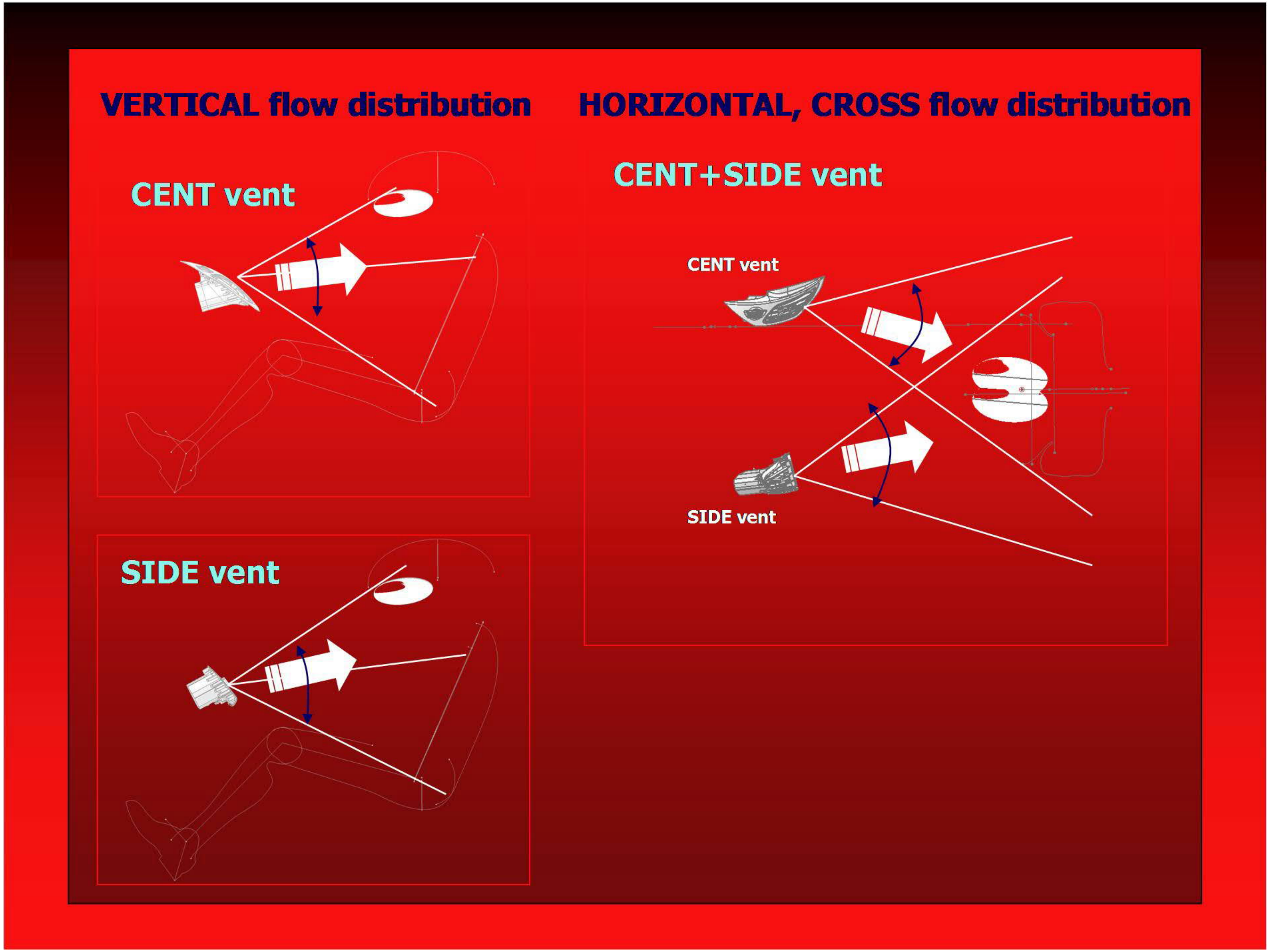
c) Phase Doppler Anemometer

At VKI (Von Kármán Institute) and at UNI Karlsruhe (125mW 632nm)

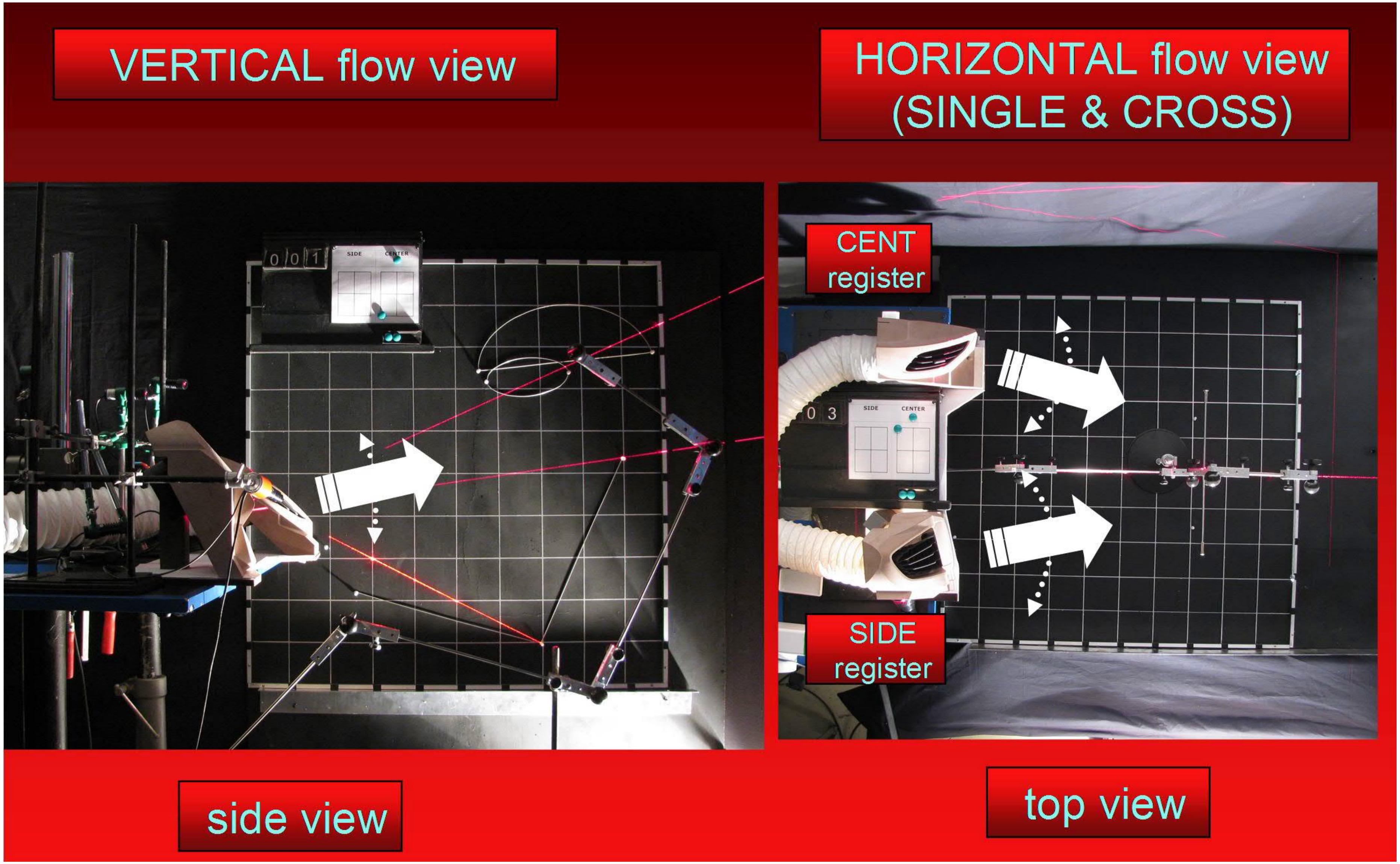
FLOW VISUALIZATION (50 - 100 mW diode)



FLOW VISUALIZATION (50 - 100mW diode)



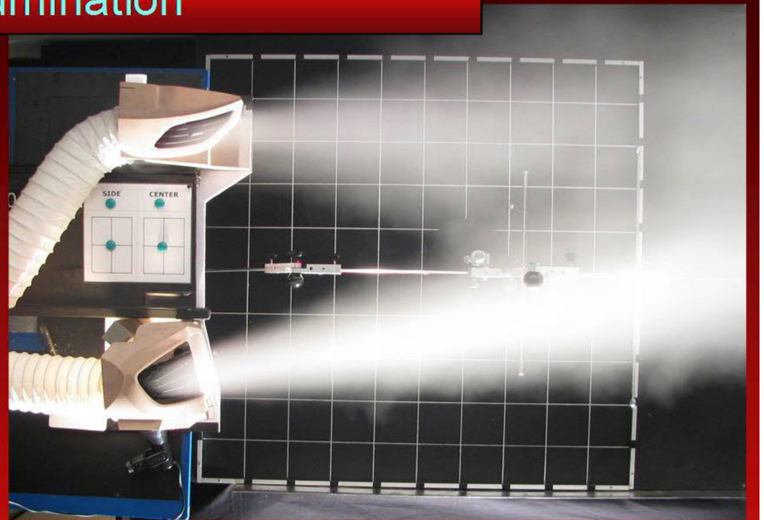
FLOW VISUALIZATION (50 – 100 mW diode)



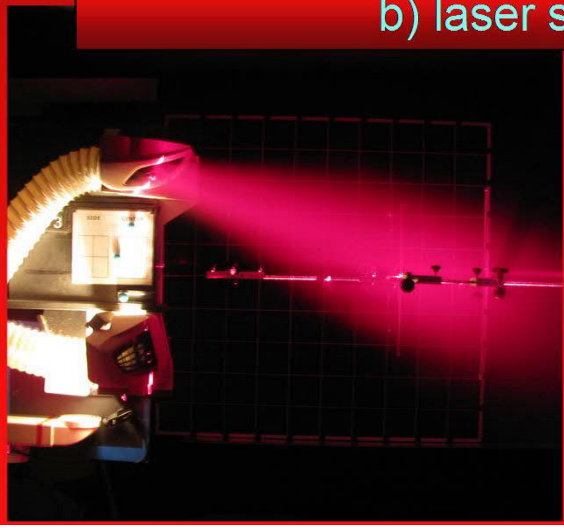
FLOW VISUALIZATION (50 – 100 mW diode)

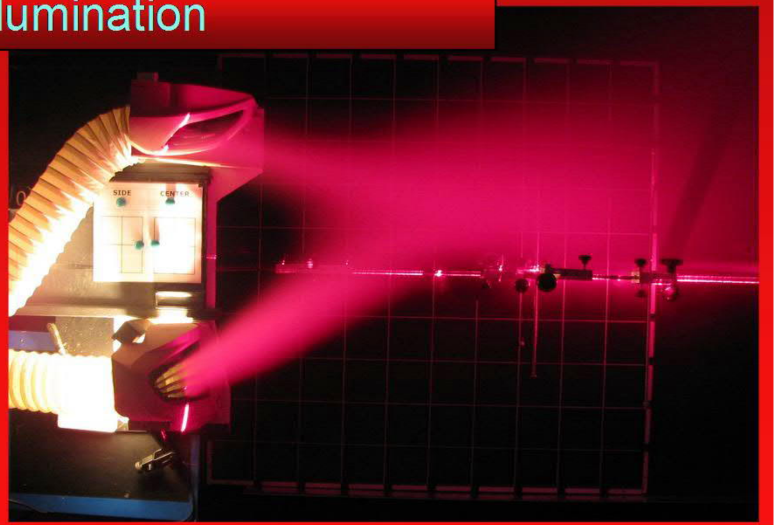
Two types of illumination are used:

a) light sheet illumination

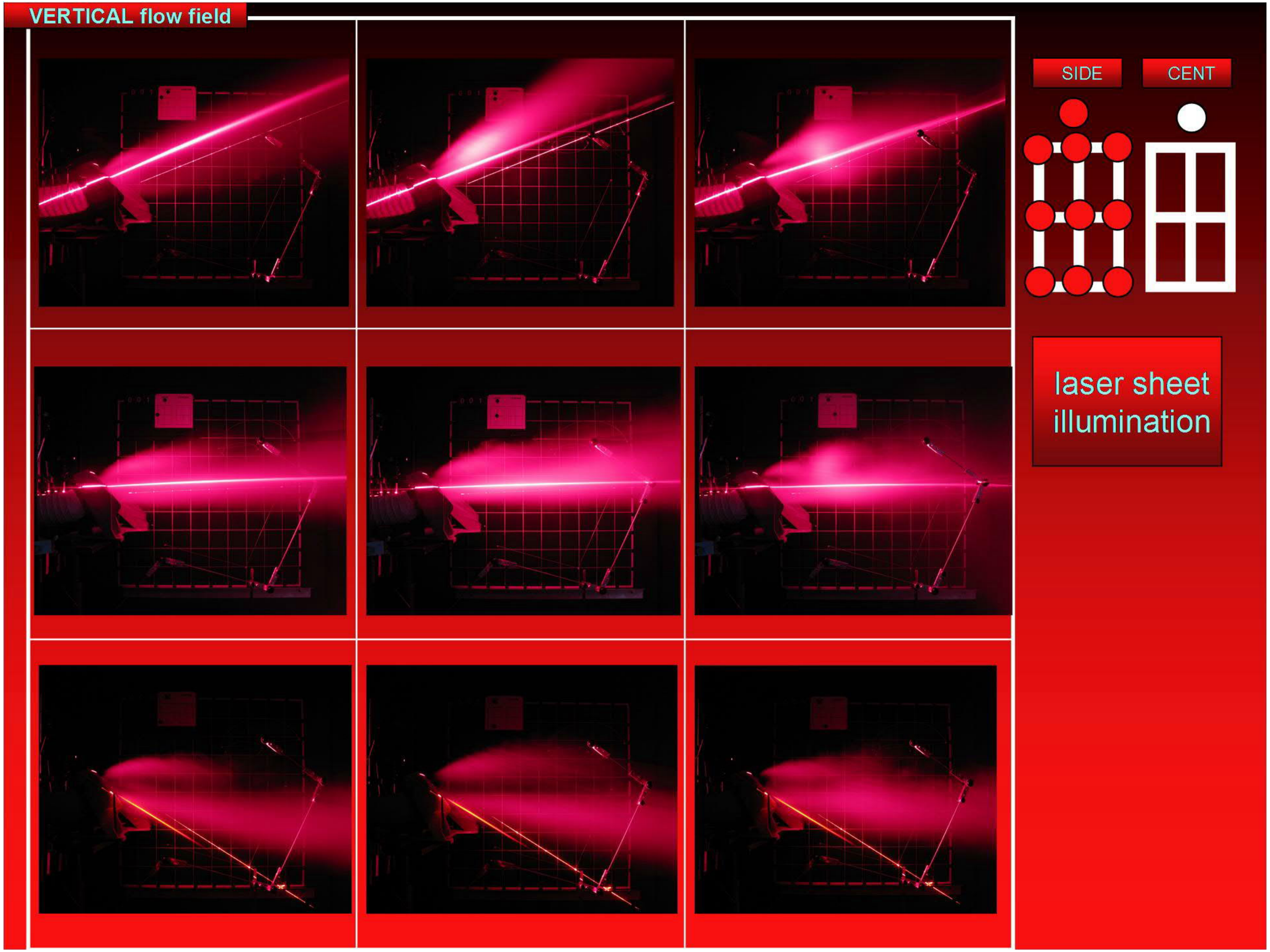


b) laser sheet illumination





FLOW VISUALIZATION (50 – 100 mW diode)



FLOW VISUALIZATION (50 – 100 mW diode)

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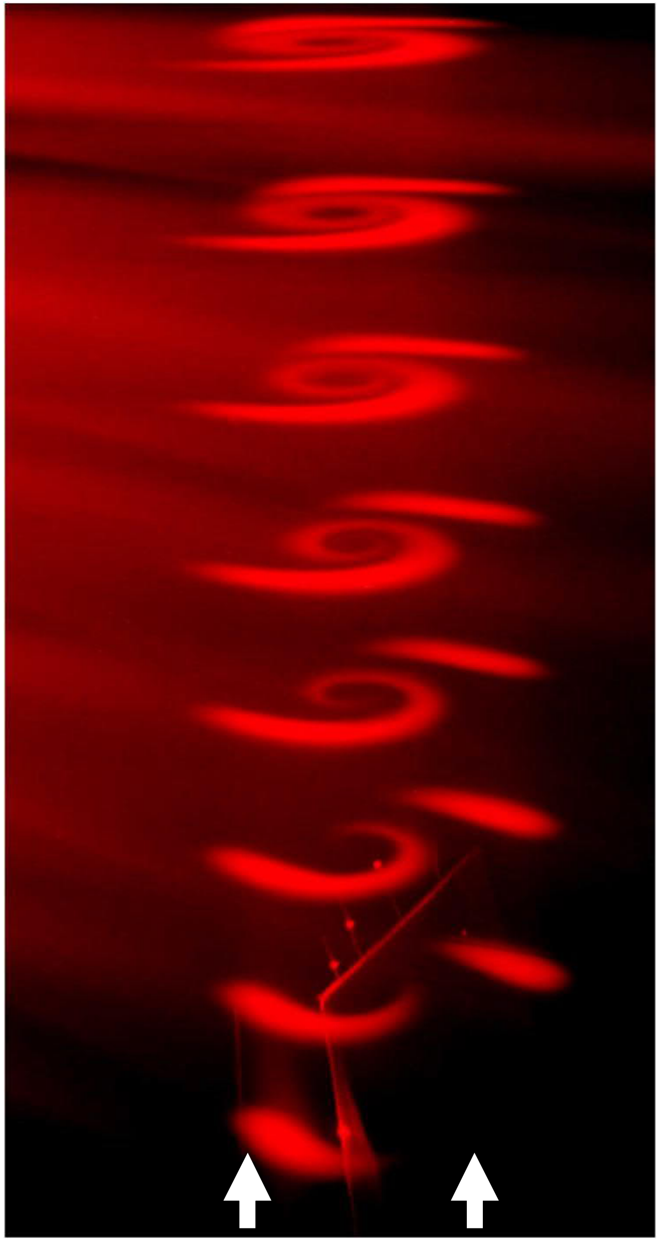
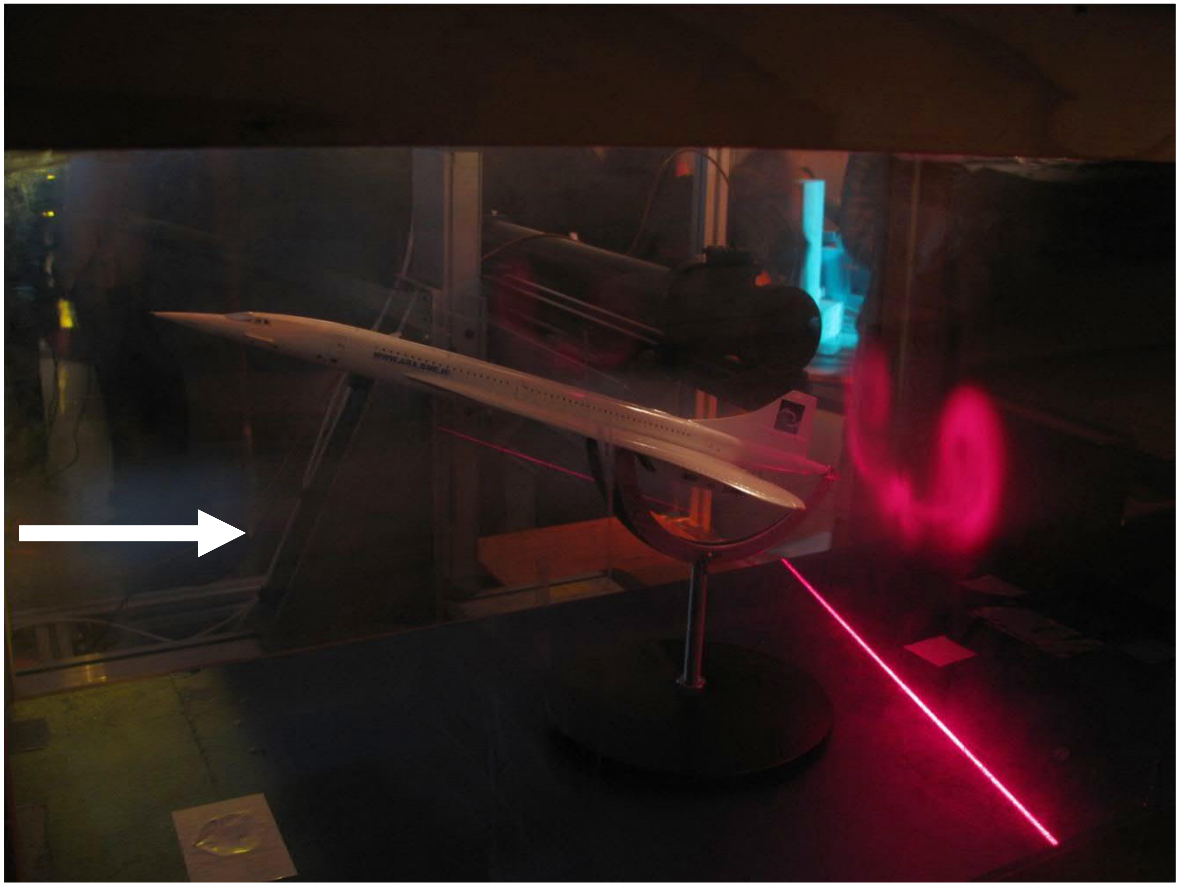
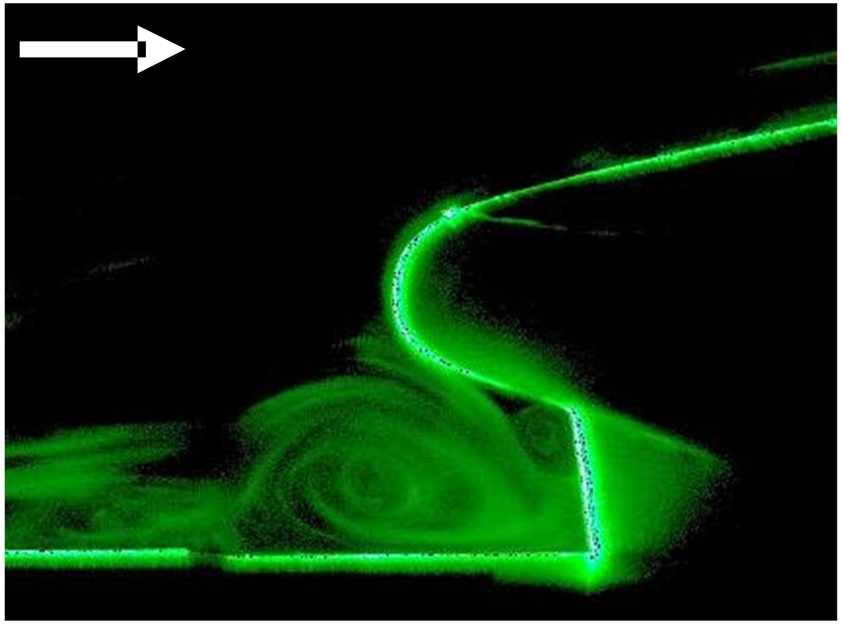
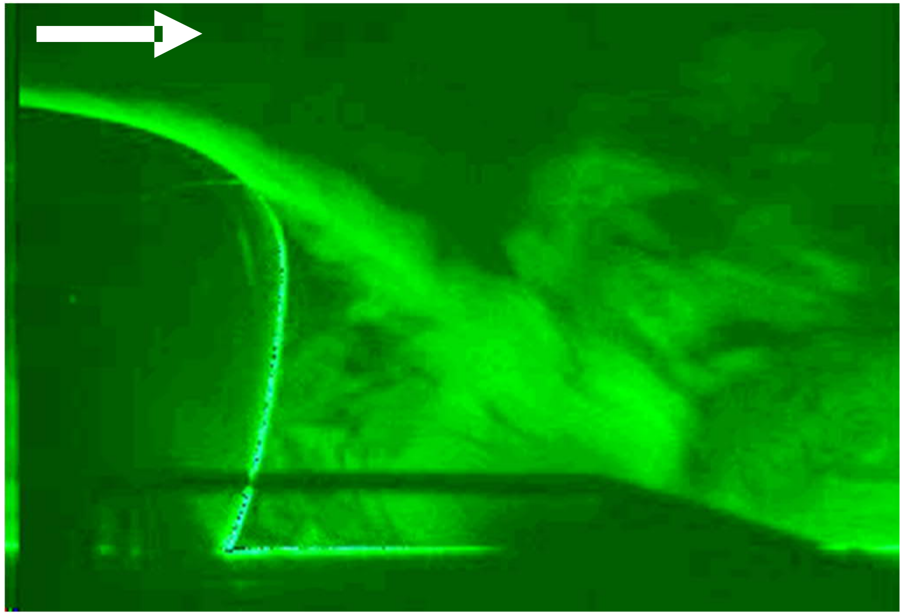


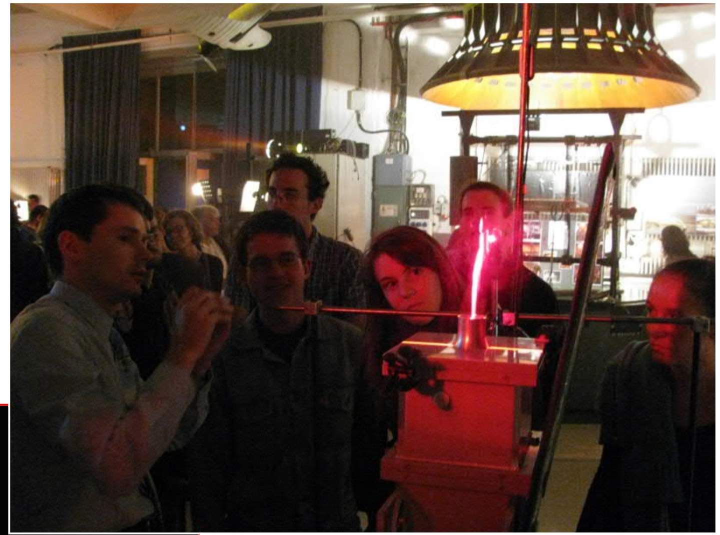


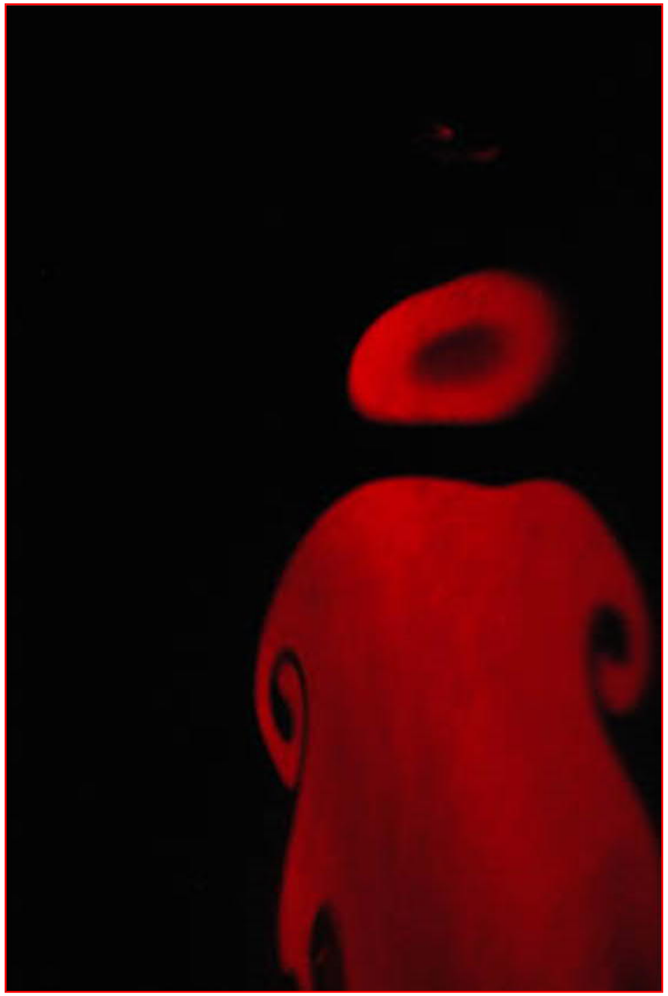
FLOW VISUALIZATION (50 – 100 mW diode)

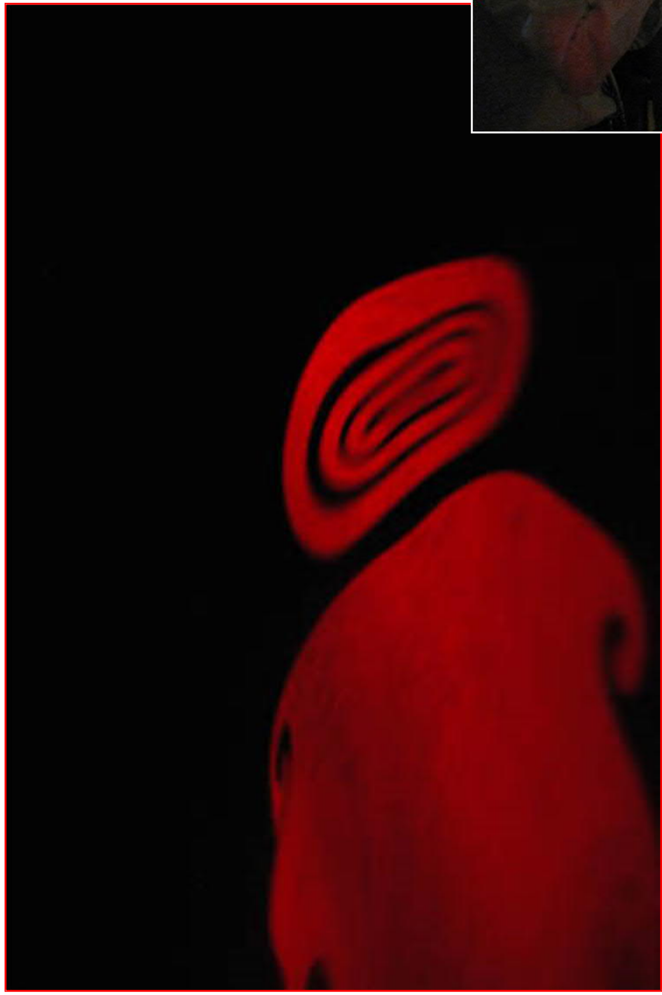




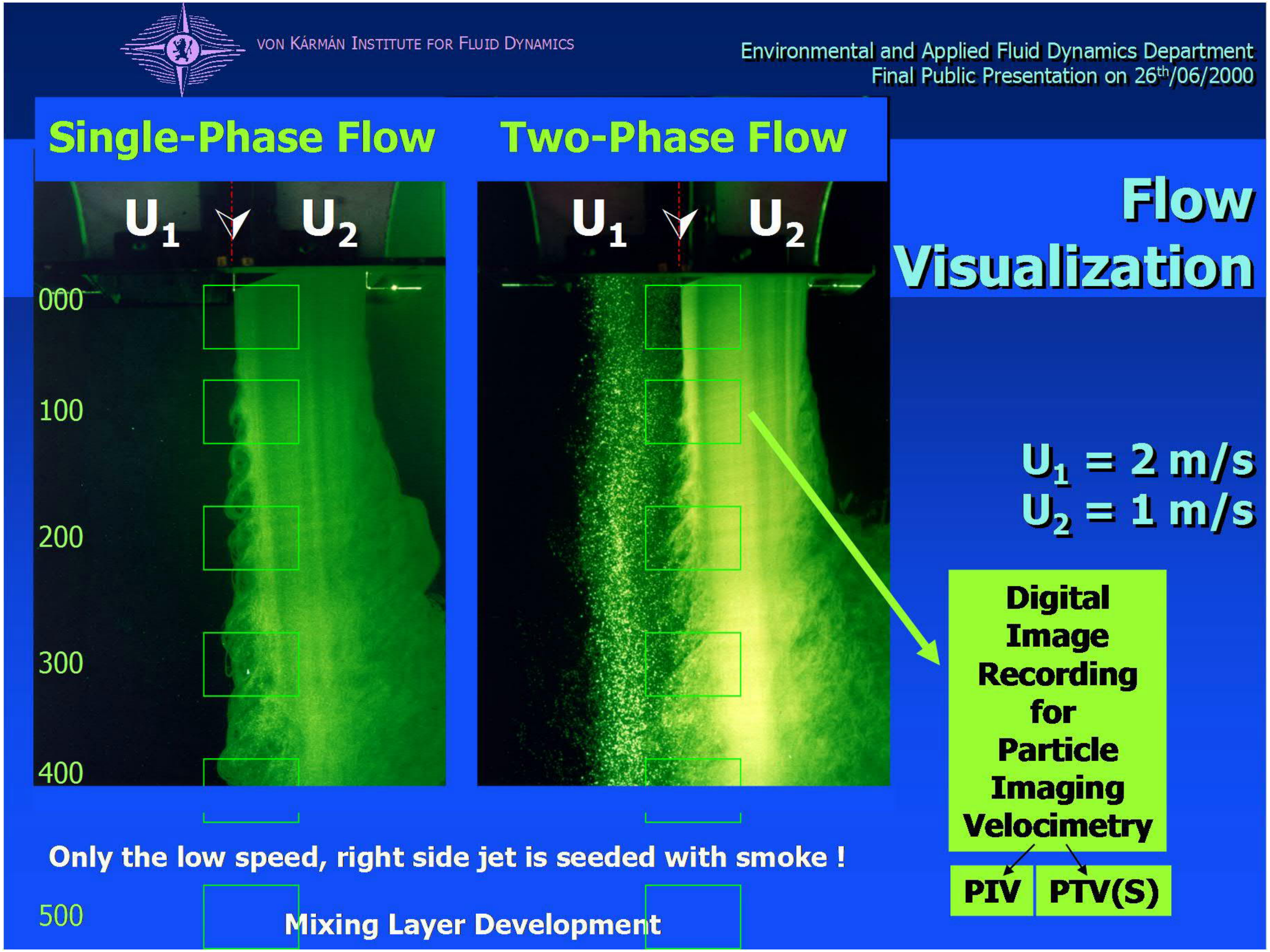
FLOW VISUALIZATION (50 – 100 mW diode)



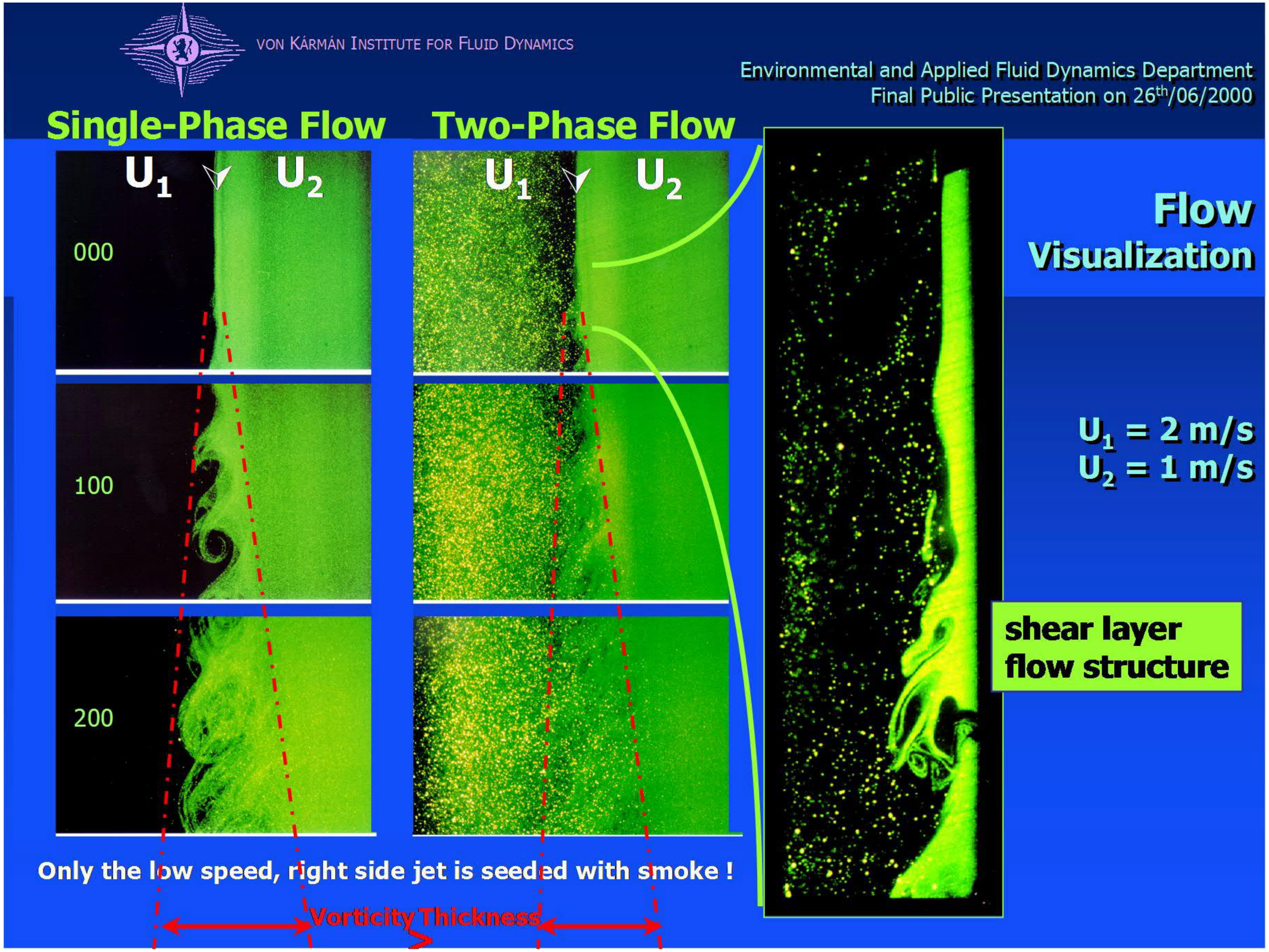




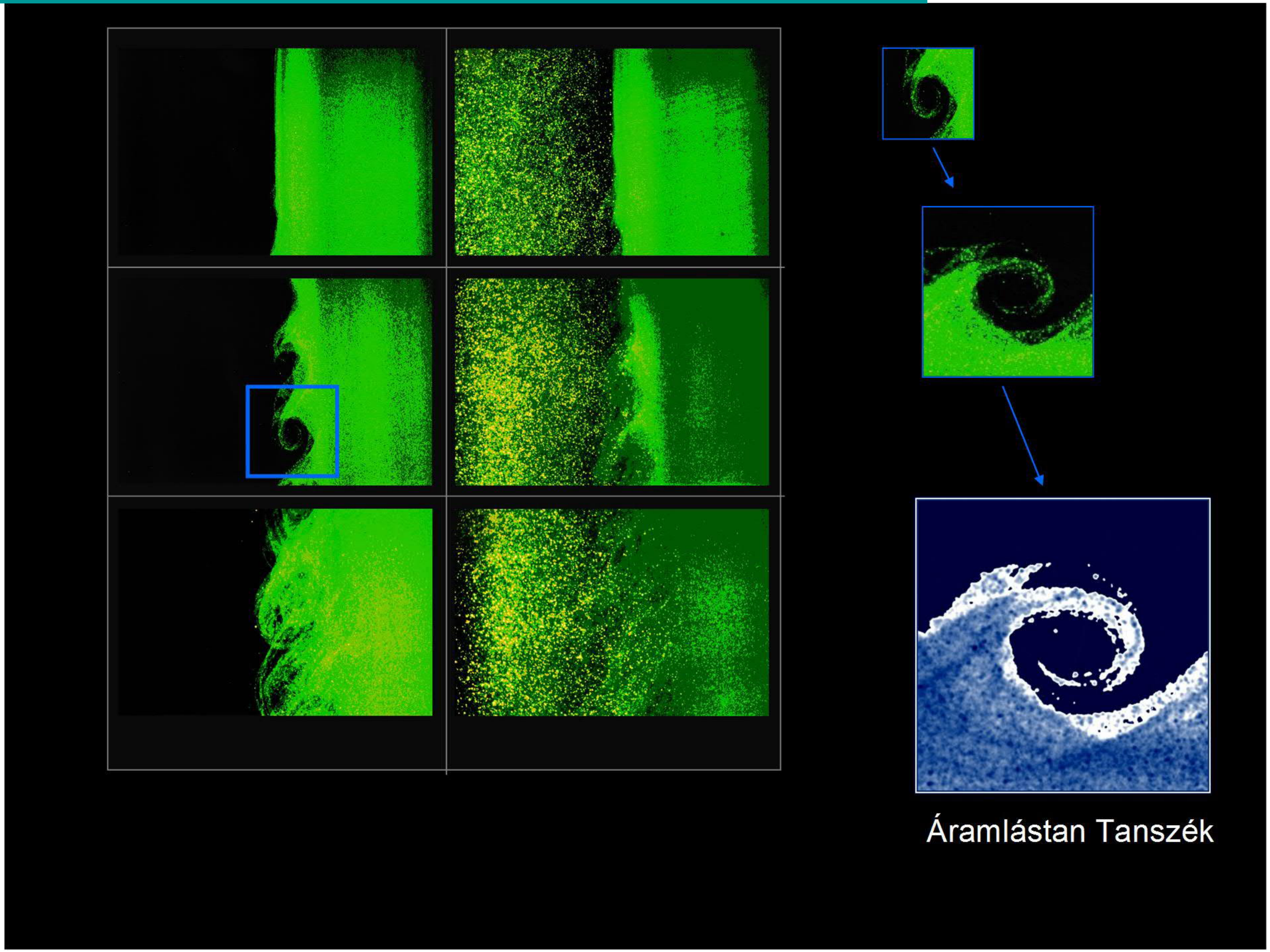
FLOW VISUALIZATION (6W: Nd:YAG, cont. mode



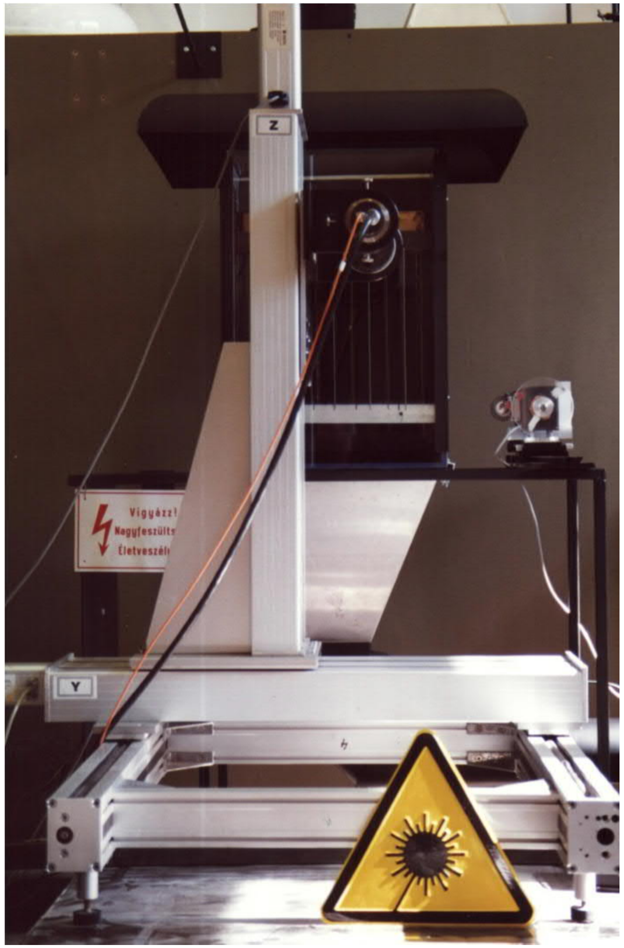
FLOW VISUALIZATION (6W Nd:YAG, cont. mode



FLOW VISUALIZATION (6W Nd:YAG, cont. mode



LASER DOPPLER ANEMOMETRY
LDV POLYTEC LDV-380 100mW diode laser
1D: only for single velocity component meas.
λ= 810 nm (infrared)
(R&D cooperation with UNI MAGDEBURG)



PARTICLES
Types and sizes of particles
BEHAVIOUR in the carrier flow
„seeding / tracer” problematic

Types of „aerosols” 0.01μm < d_p < 50μm

Dust:

size range: d ≥ 0,2 [μm]

description: solid particles, produced by breaking or attrition, abrasion, wearing of solid substances, perceptible to the eye, the diameter is larger than the wave length of light.

Smoke (fume):

size range: d ≤ 1 [μm]

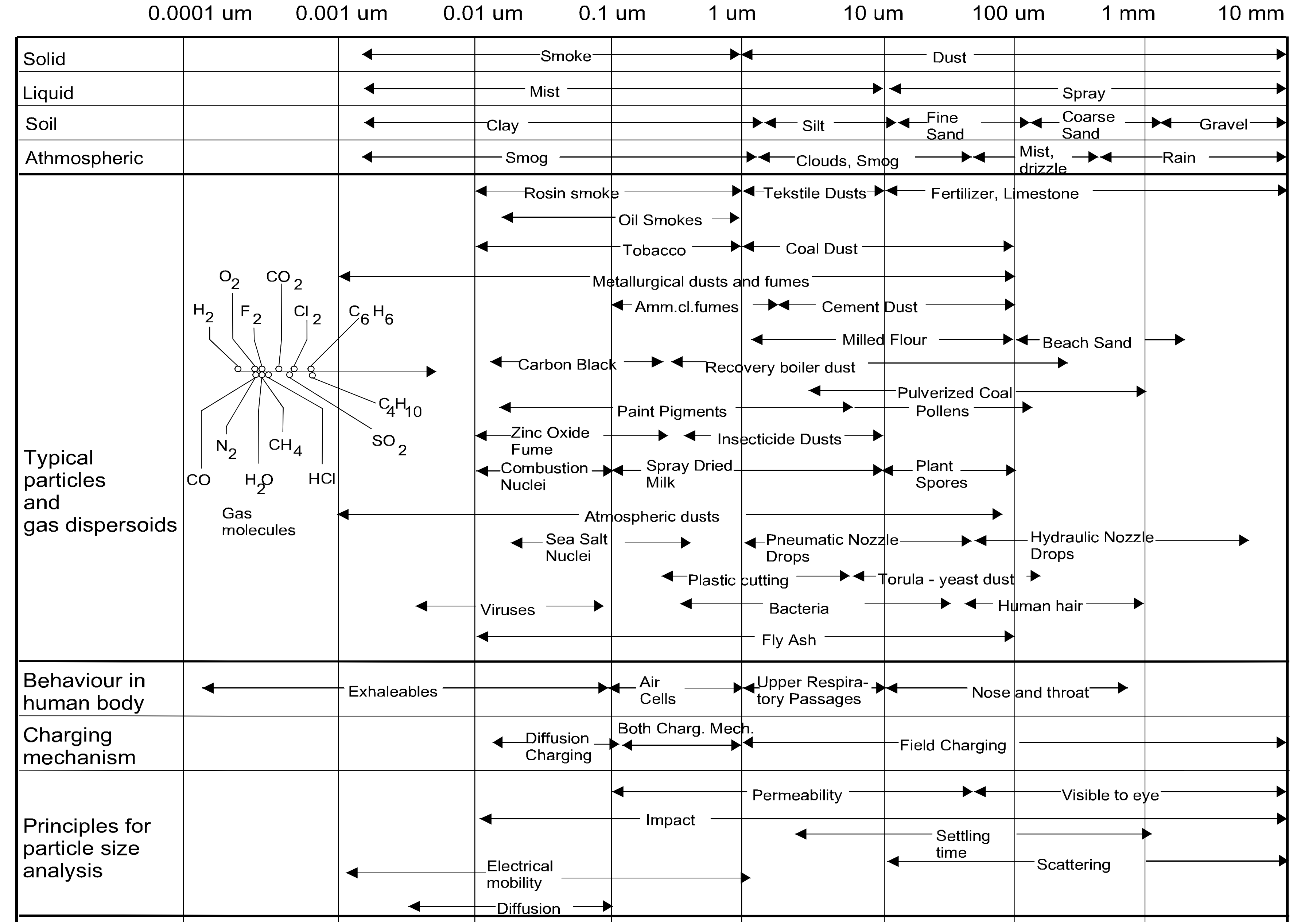
description: solid or liquid particles or droplets, originated from condensation or chemical reaction, in most cases chain-like structures. Produced at combustion, chemical processes etc.

Mist (fog):

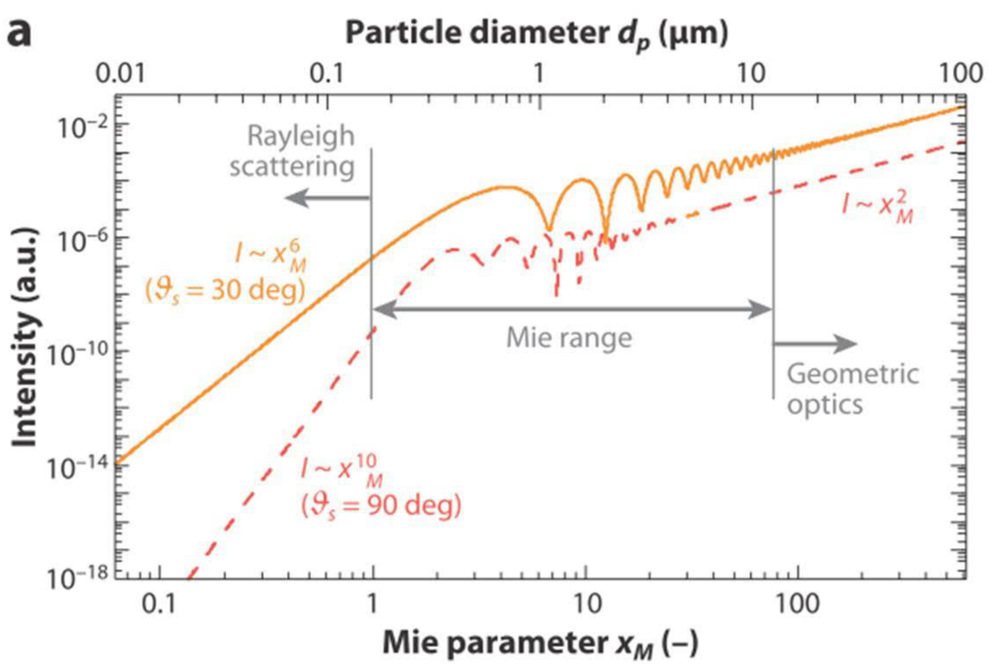
size range: 0,1 ≤ d ≤ 200 [μm]

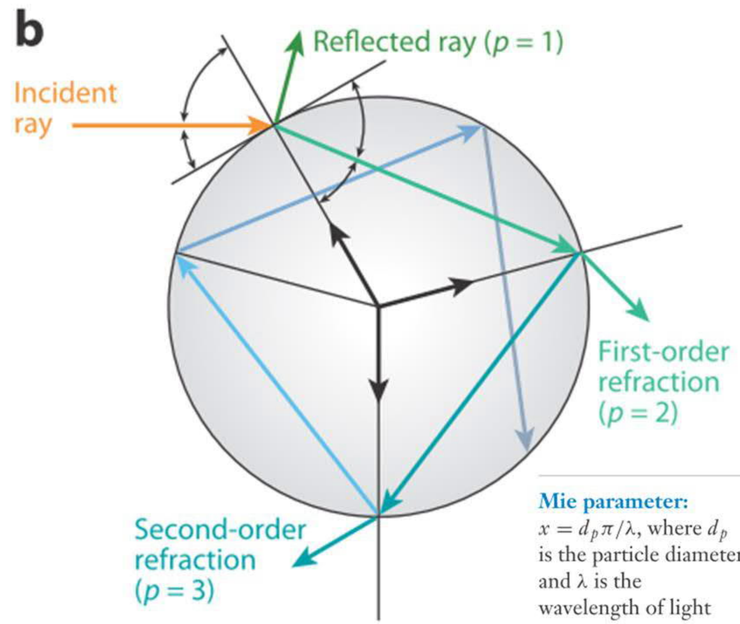
description: liquid droplets originated from steam condensation or by atomization, spraying. The mist droplets and the saturated steam of that liquid are in equilibrium state.

PARTICLES


0.0001 um
0.001 um
0.01 um
0.1 um
1 um
10 um
100 um
1 mm
10 mm
Solid
Smoke
Dust
Liquid
Mist
Spray
Soil
Clay
Silt
Fine Sand
Coarse Sand
Gravel
Athmospheric
Smog
Clouds, Smog
Mist, drizzle
Rain
Typical particles and gas dispersoids
Rosin smoke
Tekstile Dusts
Fertilizer, Limestone
Oil Smokes
Tobacco
Coal Dust
Metallurgical dusts and fumes
Amm.cl.fumes
Cement Dust
Milled Flour
Beach Sand
Carbon Black
Recovery boiler dust
Pulverized Coal
Paint Pigments
Pollens
Zinc Oxide Fume
Insecticide Dusts
Combustion Nuclei
Spray Dried Milk
Plant Spores
Atmospheric dusts
Sea Salt Nuclei
Pneumatic Nozzle Drops
Hydraulic Nozzle Drops
Plastic cutting
Torula - yeast dust
Viruses
Bacteria
Human hair
Fly Ash
O_2 CO_2 H_2 F_2 Cl_2 C_6H_6
C_4H_{10} SO_2 N_2 CH_4 CO H_2O HCl
Gas molecules
Behaviour in human body
Exhaleables
Air Cells
Upper Respiratory Passages
Nose and throat
Charging mechanism
Diffusion Charging
Both Charg. Mech.
Field Charging
Principles for particle size analysis
Permeability
Visible to eye
Impact
Settling time
Scattering
Electrical mobility
Diffusion

BASIC FUNDAMENTALS OF LIGHT SCATTERING





Mie parameter: $x = d_p \pi / \lambda$, where d_p is the particle diameter and λ is the wavelength of light

Interference: the superposition of two or more waves resulting in a new wave pattern

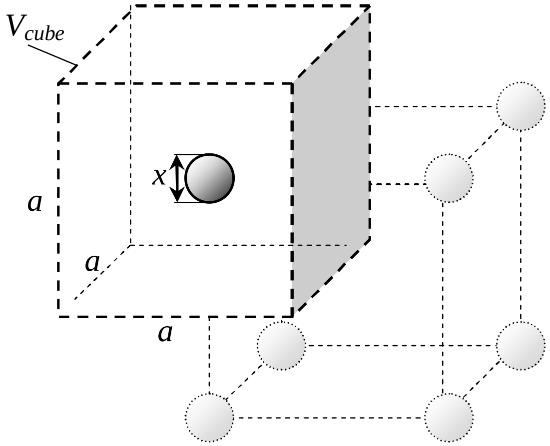
Table 1 Overview of measurement techniques for optical particle characterization

Measurement principle	Measured quantity	Measurement technique
Direct imaging	Velocity, size, shape	PIV/PTV, shadowgraphy, glare-point separation
Intensity, intensity ratio	Size, temperature, species	Extinction/absorption, modulation depth, Mie/LIF ratio, two-band/three-band LIF
Interferometry	Velocity, size, refractive index/temperature	Laser Doppler, phase Doppler, ILIDS/IPI, diffraction, rainbow refractometry, holography
Time shift	Size, velocity	Time of flight, pulse displacement, time-shift technique
Pulse delay	Size, temperature	Femtosecond laser methods
Raman scattering	Temperature, species concentration	Raman spectroscopy

Abbreviations: ILIDS, interferometric laser imaging for droplet size; IPI, interferometric particle imaging; LIF, laser-induced fluorescence; PIV, particle image velocimetry; PTV, particle tracking velocimetry.

PARTICLES

$c[g/m^3]$	$\frac{a}{x}$	N $[db/cm^3]$
10	47	350.000
1	101	35.000
0.1	218	3.500



Let's calculate the c $[kg/m^3]$ mass concentration of n particles evenly distributed in a particle-gas mixture having a volume of V_{g+p}. Let's assume that each particle is sitting in the center of a cube. (see Figure below).

The concentration can be calculated:

$$c = \frac{\sum m_p}{V_{g+p}} \cong \frac{\sum m_p}{V_{g+p}} = \frac{\sum V_p \cdot \rho_p}{V_{g+p}} = \frac{n \cdot \frac{x^3 \cdot \pi}{6} \cdot \rho_p}{n \cdot a^3} = \frac{\frac{x^3 \cdot \pi}{6} \cdot \rho_p}{a^3}$$

where c $[kg/m^3]$ mass concentration, a [m] average distance between particles, ρ_p $[kg/m^3]$ density of particles, n is number of particles.

For the average relative distance (a/x) between neighboring particles in gas we get:

$$\frac{a}{x} = \sqrt[3]{\frac{\rho_p \cdot \pi}{6 \cdot c}},$$

Conclusion:

- in case of usual particle concentration values the particle-laden flows are very dilute mixtures. (the distance between neighboring particles is very large).
- particles are present with very high number even in particle-gas mixtures having very low concentration.

PARTICLES (seeding / tracer problematic)

We need to seed, but only with particles that follow (trace) the flow field.

What doeas it mean: follow the flow?

Inertial parameter: Ψ_p = St_p :particle Stokes number

By neglecting the effect of the gravity field strength the dimensionless equation of motion of particles will turn to another form using the w_s settling velocity:

$$\frac{du'}{dt'} = \frac{l_0}{v_0^2}\underline{g} + \frac{18\mu}{x^2\rho_p}\frac{l_0}{v_0}\underline{w}' \cong \frac{18\mu}{x^2\rho_p}\frac{l_0}{v_0}\underline{w}' = \frac{g \cdot l_0}{w_s v_0}\underline{w}'$$

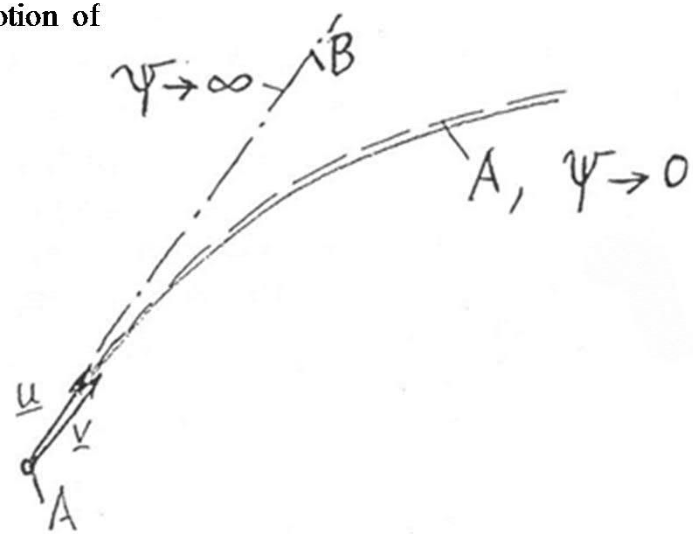
$$\boxed{\frac{du'}{dt'} = \frac{g \cdot l_0}{w_s v_0}\underline{w}'}$$

Introducing ψ inertia parameter will help us to evaluate the particle mo n gas flow:

$$\boxed{\psi = \frac{w_s v_0}{g \cdot l_0}}$$

Dimensionless momentum equation for particles with inertia parameter:

$$\boxed{\frac{d\underline{u}'}{dt'} = \frac{1}{\psi}\underline{w}' = \frac{1}{\psi}(\underline{v}' - \underline{u}')}$$



case A) dashed line in the upper figure

When ψ→0, for small (x) and/or light (ρ_p) particles, which settling velocity is small, or $w_s \to 0$, and if $(\underline{v}' - \underline{u}') \neq 0 \Rightarrow \frac{d\underline{u}'}{dt'} \to \infty$, hence particle move along the gas streamline, particle follow the carrier gas flow.

case B) dash-dot line in the upper figure

When ψ→∞, for large and/or heavy particles, which settling velocity is large, $\frac{1}{\psi} \to 0$, *consequently* $\frac{du'}{dt'} \to 0$. hence particle move along its initial path, leaving the gas streamline.

PARTICLES

Settling velocity of the particle (w_s):

Settling of particle of ρ_p density in a gas of ρ_g density:

$$w_s = \frac{x^2(\rho_p - \rho_g)g}{18\mu}$$

Correction of settling velocity due to the diffusion effect in submicron size-range:

$w_{s,corr} = Cu \cdot w_s$

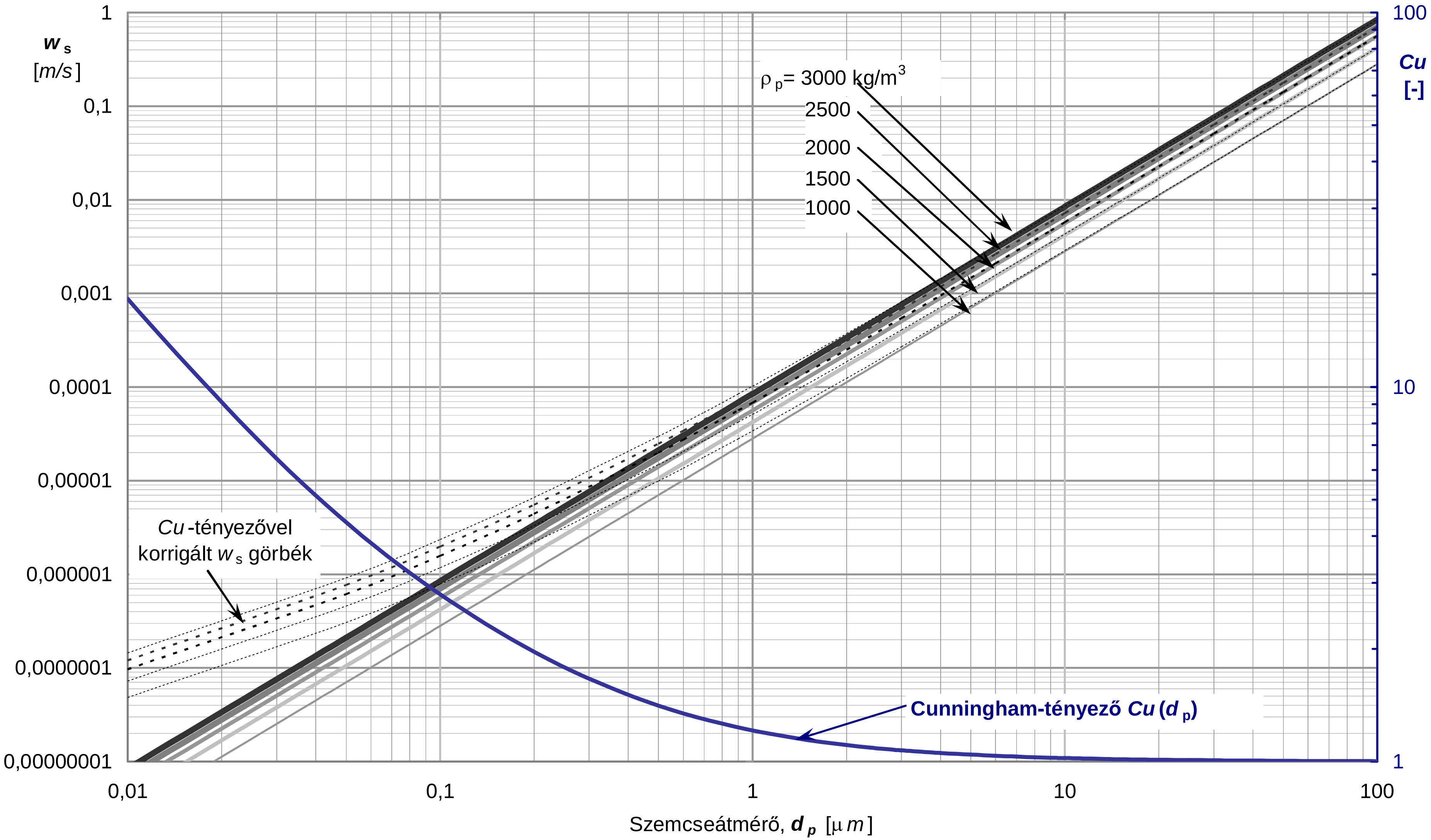
where $Cu = 1 + \frac{2\,A\,\lambda}{x}$ is the Cunningham coefficient (or Cunningham correction factor),

where A≈1.4, and λ is the mean free path of molecules, at room-temperature $\lambda = 6.5 * 10^{-2}$ μm).

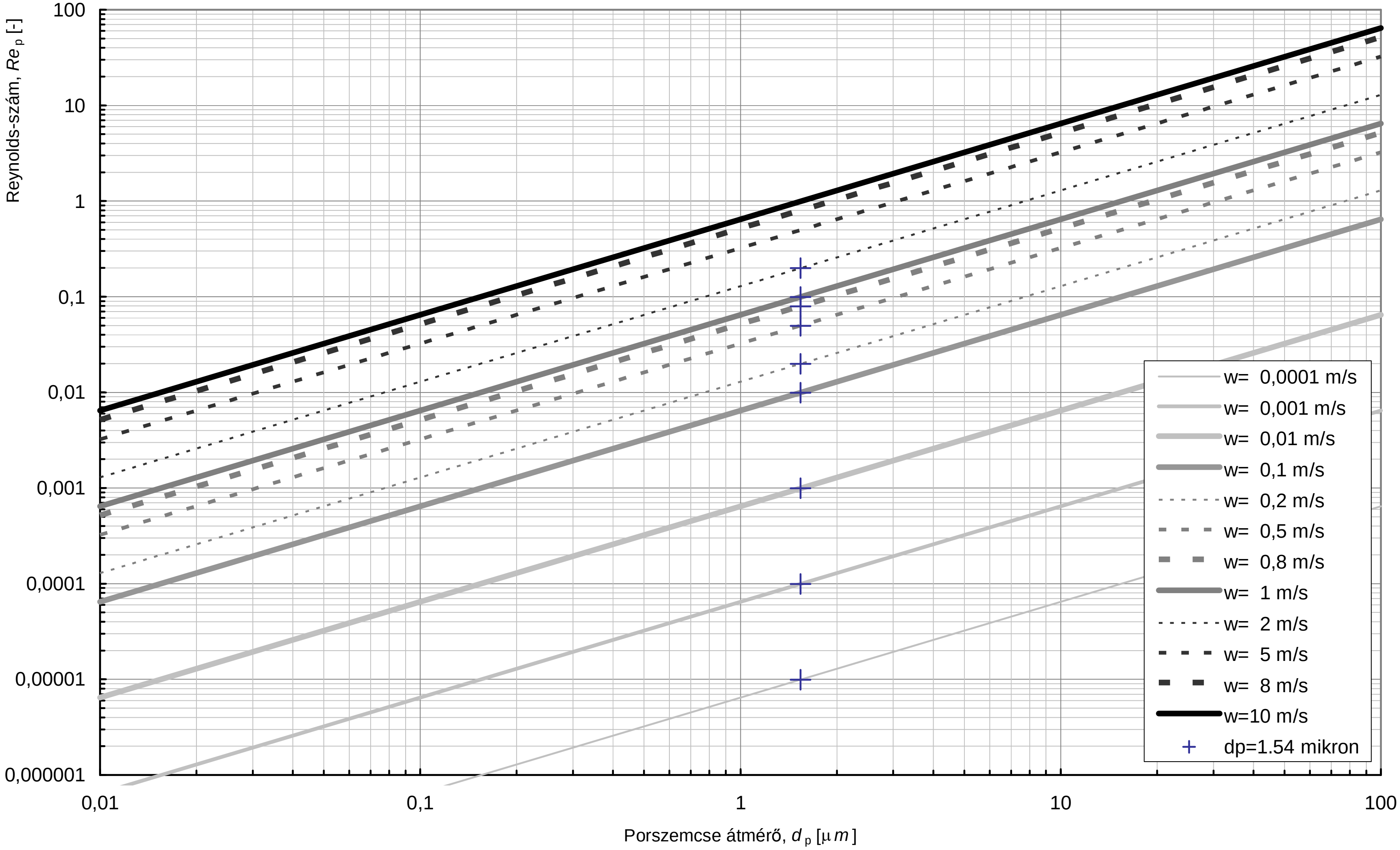
$$Cu = 1 + \frac{2\,A\,\lambda}{x}$$

$$Cu = 1 + 1{,}246 \cdot \frac{2\lambda}{d_p} + 0{,}42 \cdot \frac{2\lambda}{d_p} \cdot e^{-0{,}87\frac{2\lambda}{d_p}}$$

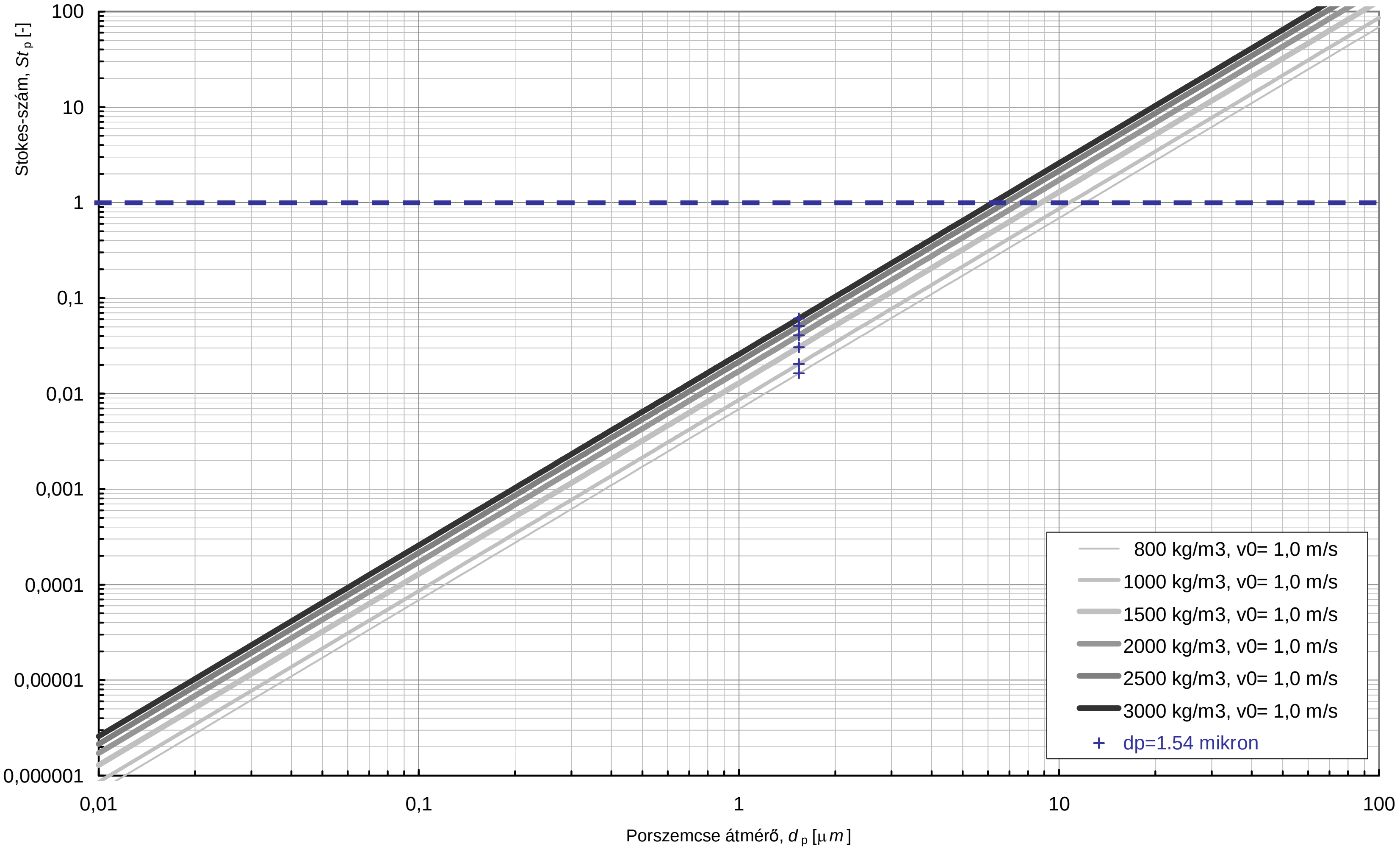
PARTICLES: setting velocity = *function of* (particle diameter)



PARTICLES: particle Reynolds-number = *function of* (particle diameter)



PARTICLES: particle Stokes-number = *function of* (particle diameter)



PARTICLES

Charatceristic parameters of the primary & secondary phase:

- carrier fluid (primary phase)
- seeding /tracer particles (secondary phase)

Volume ratio:

$$\alpha_p = \frac{V_p}{V_g} = \frac{\frac{d_p^3 \pi}{6}}{a^3} = \frac{c_p}{\rho_p}$$

Mass loading ratio:

$$M = \frac{c_p}{\rho_g} = \alpha_p \frac{\rho_p}{\rho_g}$$

$$\frac{M}{\alpha_p} = \frac{\rho_p}{\rho_g}, \text{ or } \frac{\alpha_p}{M} = \frac{\rho_g}{\rho_p}$$

where:

c_p: particle mass concentration

ρ_g: density of gas (carrier phase)

ρ_p: density of particle (material)

α_p		ρ_p [kg/m^3]		
		800	**1500**	**2500**
c_p [g/m^3]	**0,0001**	$1{,}3 \cdot 10^{-10}$	$6{,}7 \cdot 10^{-11}$	$4{,}0 \cdot 10^{-11}$
	0,001	$1{,}3 \cdot 10^{-9}$	$6{,}7 \cdot 10^{-10}$	$4{,}0 \cdot 10^{-10}$
	0,01	$1{,}3 \cdot 10^{-8}$	$6{,}7 \cdot 10^{-9}$	$4{,}0 \cdot 10^{-9}$
	0,1	$1{,}3 \cdot 10^{-7}$	$6{,}7 \cdot 10^{-8}$	$4{,}0 \cdot 10^{-8}$
	1	$1{,}3 \cdot 10^{-6}$	$6{,}7 \cdot 10^{-7}$	$4{,}0 \cdot 10^{-7}$
	10	$1{,}3 \cdot 10^{-5}$	$6{,}7 \cdot 10^{-6}$	$4{,}0 \cdot 10^{-6}$
	100	$1{,}3 \cdot 10^{-4}$	$6{,}7 \cdot 10^{-5}$	$4{,}0 \cdot 10^{-5}$

M		ρ_g[kg/m^3]		
		0,8	**1,0**	**1,2**
c_p [g/m^3]	**0,0001**	$1{,}3 \cdot 10^{-7}$	$1{,}0 \cdot 10^{-7}$	$8{,}3 \cdot 10^{-8}$
	0,001	$1{,}3 \cdot 10^{-6}$	$1{,}0 \cdot 10^{-6}$	$8{,}3 \cdot 10^{-7}$
	0,01	$1{,}3 \cdot 10^{-5}$	$1{,}0 \cdot 10^{-5}$	$8{,}3 \cdot 10^{-6}$
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	1	$1{,}3 \cdot 10^{-3}$	$1{,}0 \cdot 10^{-3}$	$8{,}3 \cdot 10^{-4}$
	10	$1{,}3 \cdot 10^{-2}$	$1{,}0 \cdot 10^{-2}$	$8{,}3 \cdot 10^{-3}$
	100	$1{,}3 \cdot 10^{-1}$	$1{,}0 \cdot 10^{-1}$	$8{,}3 \cdot 10^{-2}$

PARTICLES

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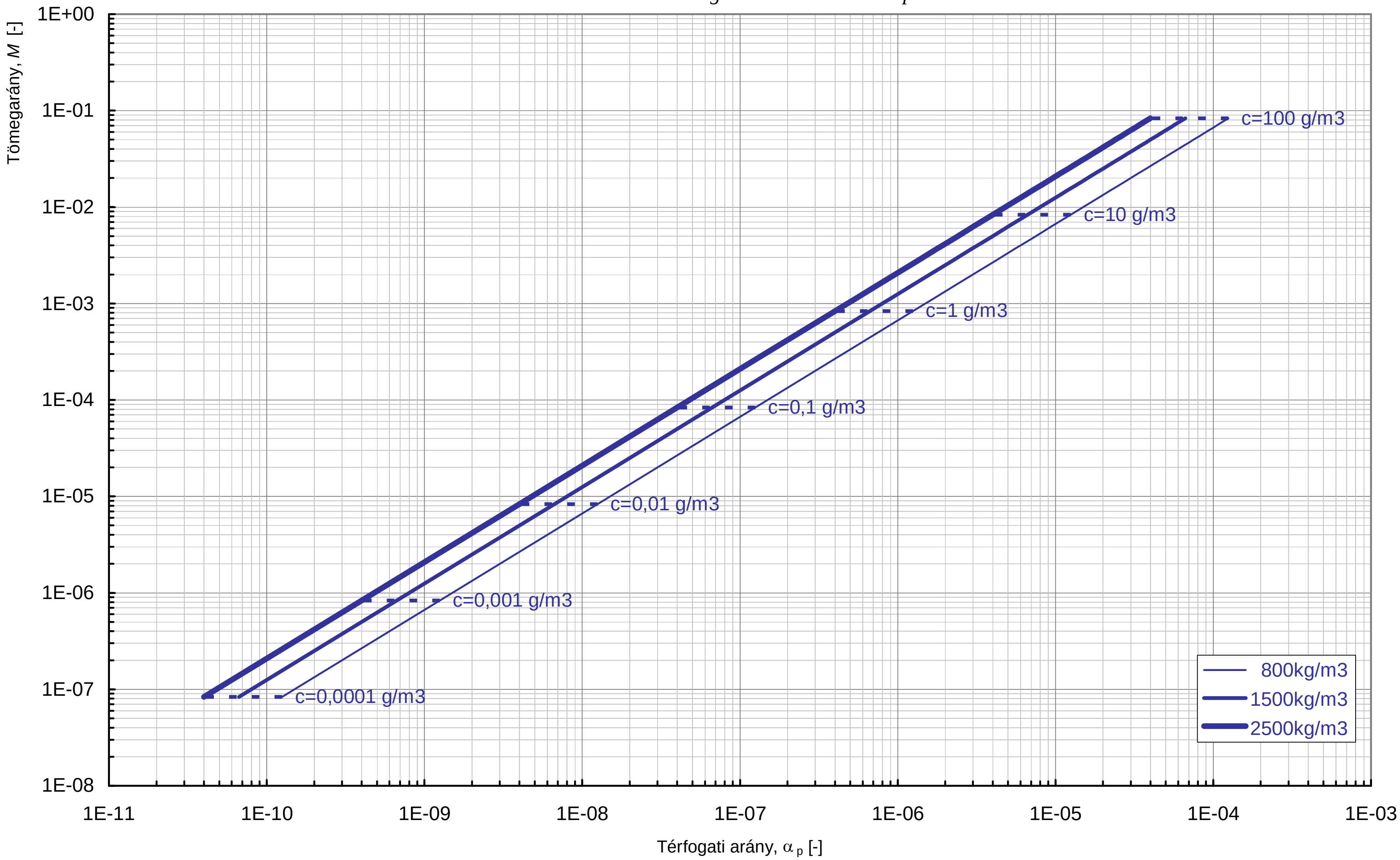
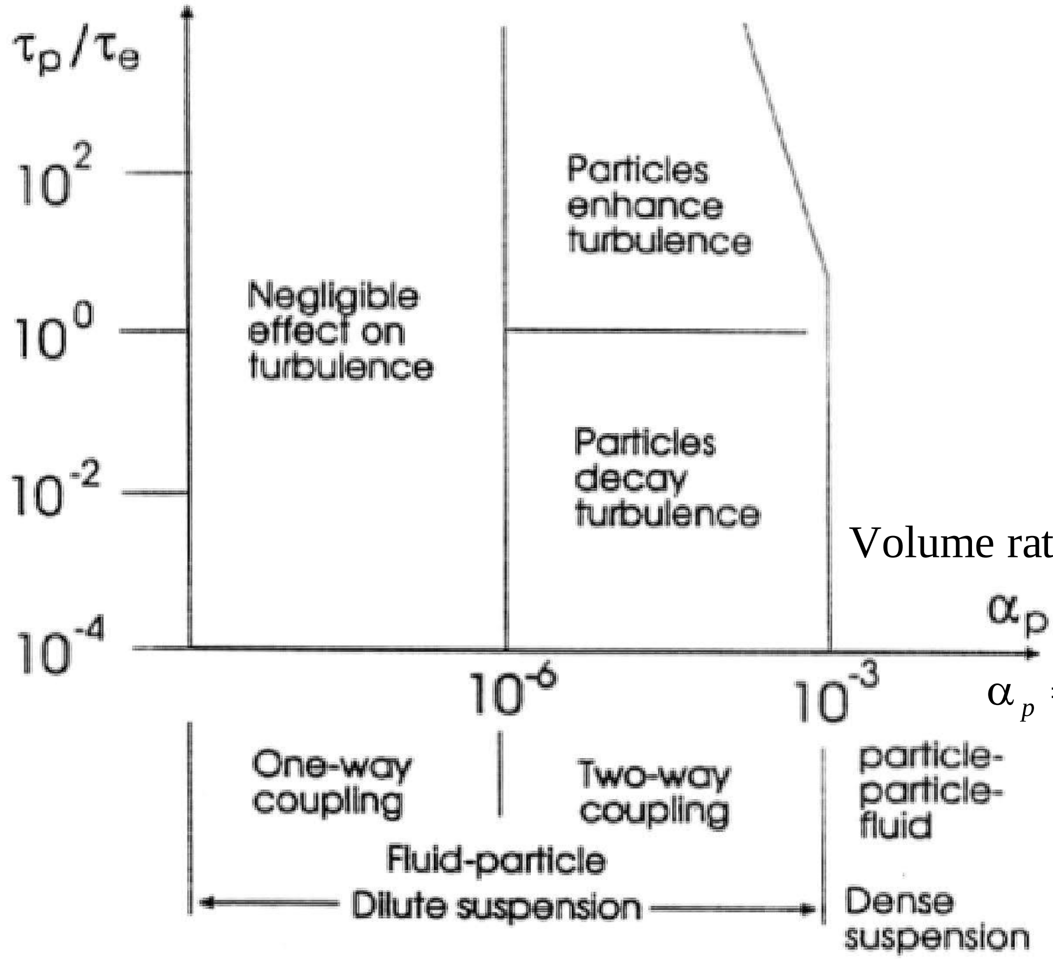


PARTICLES

particle
Stokes-number
St_p



Volume ratio:

$$\alpha_p = \frac{V_p}{V_g} = \frac{\frac{d_p^3 \pi}{6}}{a^3} = \frac{c_p}{\rho_p}$$

ELGHOBASHI (1994): „Turbulence modulation map": particle STOKES-number ($St_p=\tau_p/\tau_e$) in function of the α_p

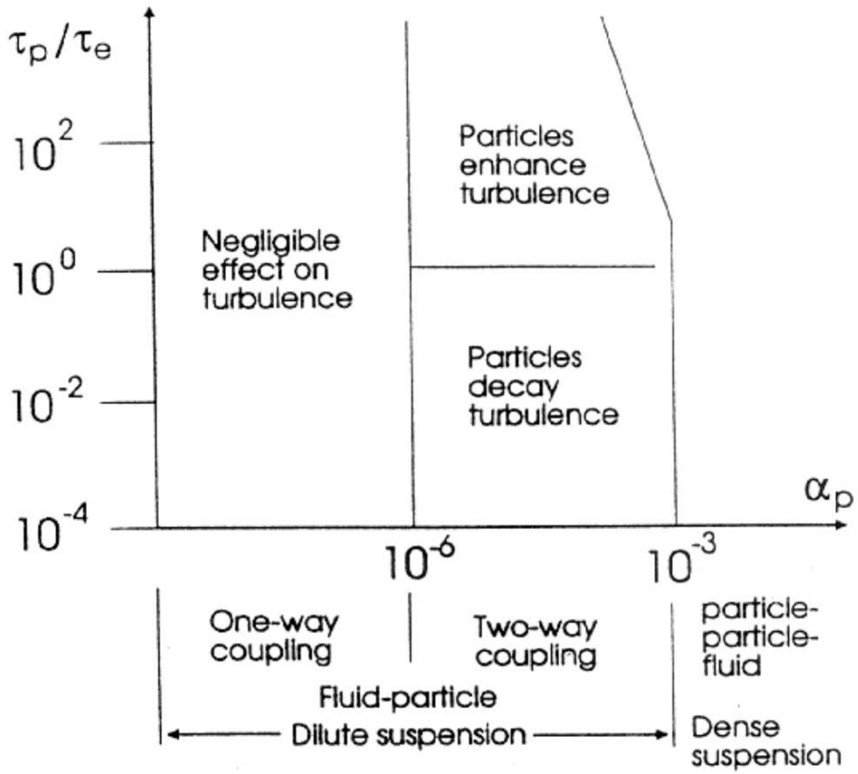
τ_p: characteristic (response) time of the particle

τ_e: characteristic time of the carrier fluid

dilute mixtures: $\alpha_p < 10^{-3}$

dense mixtures: $\alpha_p > 10^{-3}$

PARTICLES' influence on turbulence of the carrier flow



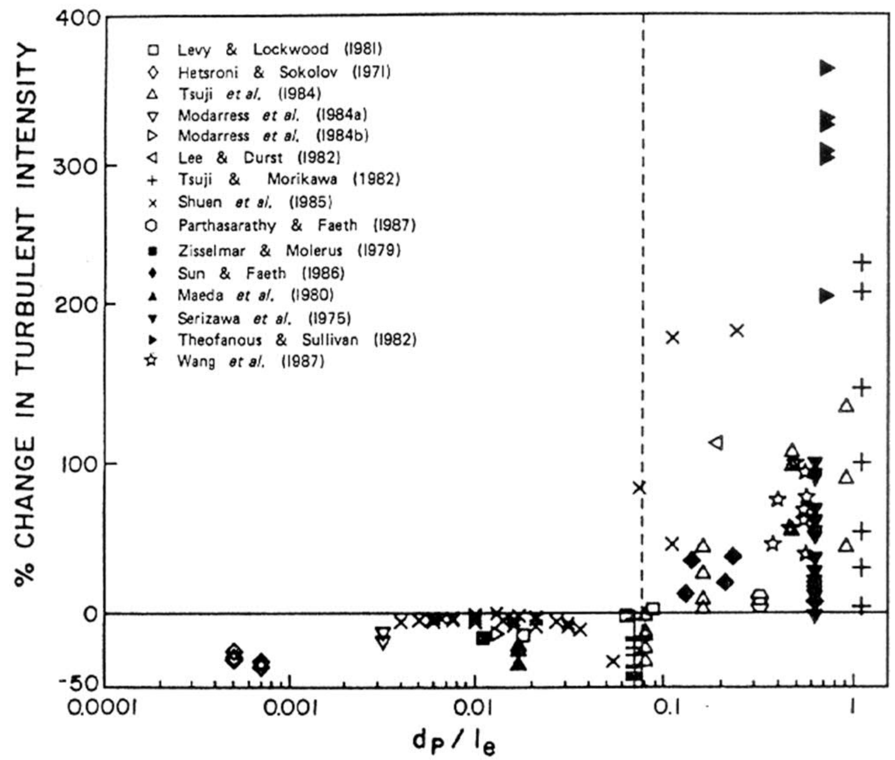


Figure 2. Change in turbulent intensity as function of length scale ratio.

[ELGHOBASHI, 1994]

[GORE and CROWE, 1989]

PARTICLES

Table 3. Seeding particles in gas flows.

Material	d_p (μm)	Laser	Pulse energy, pulse time	Light sheet w (mm)	Light sheet t (mm)	Reference
TiO_2 (m = 2.6, ρ = 3500 kg m^{-3})	<1	Nd:YAG	10 mJ, 20 ns	15	0.3	Reuss *et al* (1989)
TiO_2, ZrO_2	0.7–1	Nd:YAG	110 mJ, 12 ns			Paone *et al* (1996)
Al_2O_3 (m = 1.76,	0.3	Nd:YAG	400 mJ		0.2	Muniz *et al* (1996)
ρ = 3970 kg m^{-3})	3	Nd:YAG	9 mJ, 6 ns			Anderson *et al* (1996)
	0.8	Ruby	20 ns	150	$\simeq$1	Krothapalli *et al* (1996)
Polycrystalline	30	Nd:YAG	135 mJ, 6 ns			Grant *et al* (1994)
Glass	30	Ruby	30 mJ, 30 ns			Schmidt and Löffler (1993)
Oil smoke	1	Ruby	5 J			Stewart *et al* (1996)
Corn oil	1–2	Nd:YAG	100 mJ			Jakobsen *et al* (1994)
Oil	1–2	Nd:YAG	120 mJ		0.4	Westerweel *et al* (1993)
Olive oil (m = 1.47, ρ = 970 kg m^{-3})	1.06	Nd:YAG	70 mJ, 16 ns	200	0.5	Höcker and Kompenhans (1991) Fischer (1994) Raffel *et al* (1996)

PARTICLES

Table 4. Seeding particles in liquid flows.

Material	d_p (μm)	Laser	CW power or energy, time	Light sheet w (mm)	t (mm)	Reference
TiO_2	3	Nd:YAG				Longmire and Alahyari (1994)
Al_2O_3	9.5	Ruby	2 J, 30 ns	100	0.8	Liu *et al* (1991)
Conifer pollen	50–60	Ar ion	1-2 W			Westergaard *et al* (1993)
(ρ = 1000 kg m^{-3})						McCluskey *et al* (1995)
						Gallagher and McEwan (1996)
Polymer	30	Ar ion	0.5–5 W		0.5	Draad and Westerweel (1996)
(ρ = 1030 kg m^{-3})						McCluskey *et al* (1996)
Phosphorescent polymer	80	Ar ion	5 W		1	Willert and Gharib (1991)
Fluorescent	50	Nd:YAG				Hart (1996)
	20	Cu vapour	45 W		1	Roth *et al* (1995)
Polystyrene	500					Khoo *et al* (1992)
(ρ = 1050 kg m^{-3})	15	Ruby	25 mJ, 20 ns			Zhang *et al* (1996)
Thermoplastic	6	Nd:YAG		50	2	Hassan *et al* (1994)
(ρ = 1020 kg m^{-3})						
Reflective	60	Ar ion	18 W			Grant *et al* (1992)
(ρ = 1010 kg m^{-3})	30	Ar ion	12–18 W	200		Grant and Wang (1994)
Metallic coated	4	Ar ion	2 W		2	Magness *et al* (1993)
	14	Ar ion			1	Johari *et al* (1996)
Microspheres	<30	Ar ion				Graham and Soria (1994)
(ρ = 700 kg m^{-3})						
H_2 bubbles		Ar ion	1 W		0.3	Dieter *et al* (1994)

PARTICLES

Table 2. Particle response in turbulent flow (η = 0.99).

Particle	ρ_p (kg m^{-3})	Gas (10^5 Pa)	Density ratio s	Viscosity ν (m^2 s^{-1})	f_c (kHz)	Sk_c	d_p (μm)
TiO_2	3500	Air	2950	1.50×10^{-5}	1	0.0295	1.44
		(300 K)			10		0.45
Al_2O_3	3970	Flame	20250	3.00×10^{-4}	1	0.0113	2.46
		(1800 K)			10		0.78
Glass	2600	Air	2190	1.50×10^{-5}	1	0.0342	1.67
		(300 K)			10		0.53
Olive oil	970	Air	617	1.45×10^{-5}	1	0.0645	3.09
		(220 K)			10		0.98
Microballoon	100	Air	84.5	1.50×10^{-5}	1	0.1742	8.50
		(300 K)			10		2.69

the Stokes number Sk, a characteristic non-dimensional frequency of the particle response. Sk is defined here as

$$Sk = \left(\frac{\omega}{\nu}\right)^{1/2} d_p \qquad (6)$$

SEPARATE SLIDES!

1. LDA (ppt, Dantec)
2. PIV (ppt, VKI) + Stereo PIV (Dantec)
3. PTV(S) (ppt, PDF, VKI – pivneta course)

Suggested hadout, books, literatures:
Website of Dept. Fluid Mech for this subject:
http://www.ara.bme.hu/oktatas/tantargy/NEPTUN/BMEGEATMW03/2011-2012-II/

Springer Handbook of Experimental Fluid Mechanics
(Eds.: Tropea, Yarin, Foss), ISBN 978-3-540-25141-5 (Springer-Verlag Berlin 2007)
Measurement Techniques in Fluid Dynamics – An Introduction
(VKI Lecture Series 2001)
Advanced measurement techniques
(VKI Lecture Series, 1998.)
Optical velocity measurements
(VKI Lecture Series 1994.
Laser Doppler Velocimetry
(Dantec website: www.dantecdynamics.com)
Particle Image Velocimetry - A Practical Guide
(Eds.: Raffel/Willart/Kompenhans) Springer-Verlag, Berlin 1998, ISBN 978-3-540-72307-3
Flow Visualization - Techniques and Examples
(Eds.: Smits&Lim), Imperial College Press, London, 2003
Laser Doppler and Phase Doppler Measurement Techniques
(Albrecht, Damaschke, Borys, Tropea: Springer-Verlag)
Laser Techniques and Applications in Fluid Mechanics
(Springer Verlag ISBN 3-540-56879-4)
Speckle Metrology (Eds: R.S. Sirohi, , Marcel Dekker, New York, 1993, ISBN 0-82478-932-6
Holographic Interferometry: Principles and Methods
(Kreis) Akademie Verlag, 1996, ISBN 3-05501-644-0
Handbook of Holographic Interferometry
(Kreis) Wiley-VCH, Weinheim 2005, ISBN 3-527-40546-1
Optical Measurement Techniques and Applications
(Ed. Pramod K. Rastogi); Artech House 1997, ISBN 0-89006-516-0

PIV systems:
conventional 2D PIV
stereo PIV
High speed (Time Resolved) PIV
micro PIV

ABILITY of the various systems:

•2D / Planar system provides velocity measurement in a single plane, normally at frame rates up to 15 image pairs/second.

•Stereo / 3D systems use a pair of cameras to provide stereo / 3D measurement of velocity.

•High speed / time resolved products use high speed cameras and high repetition rate, double pulse lasers to take thousands of image pairs per second to provide time resolved velocity data.

•Micro systems view via a time resolved system and provide flow measurement in microfluidic devices.

CVL: Copper vapour laser
-ideal for high-speed, high-power imaging laser. (short pulse, high beam quality, high power beam) makes it ideal for imaging applications at frequencies 10kHz requiring light-sheets or area illumination.

Applications
-High Speed Imaging
-Time Resolved PIV
-Spray Pattern Measurement
-Flow Visualisation

Specifications:

Laser Type: Copper Vapour Laser

Average Power: 20-35W (depending on model)

Pulse Duration: 25ns

Wavelength: 511nm

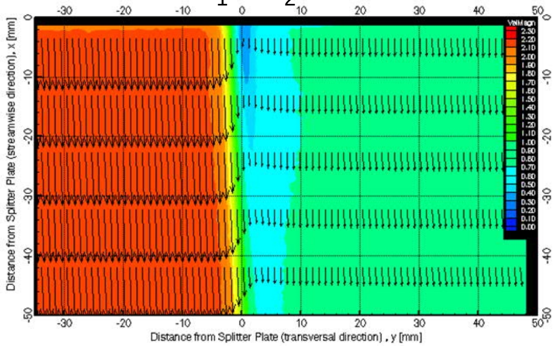
Frequency: 3.5-20KHz continuous running frequency. Burst mode frequencies from 0 to 50KHz available.

Timing Jitter: <2-5ns (depending on model)

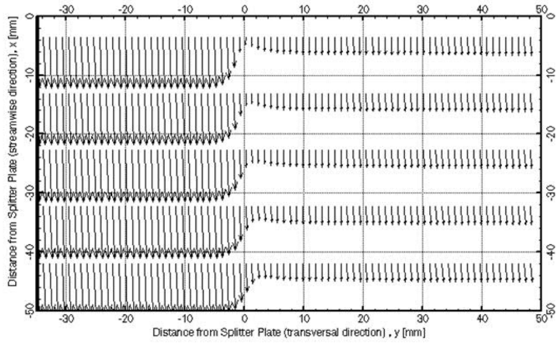
PIV

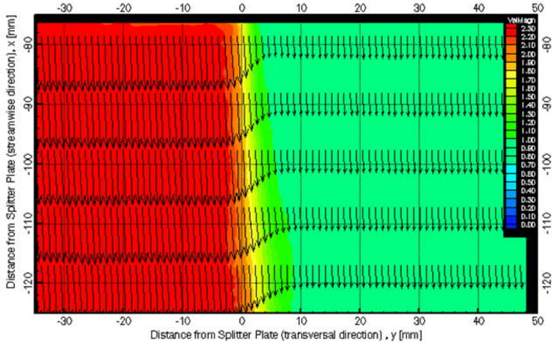
Instantaneous mean ($v_{x;}v_y$)

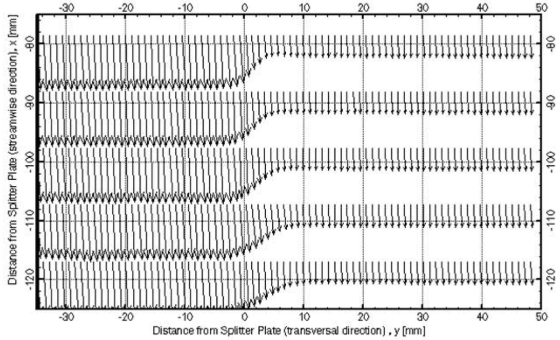
U_1 ▼ U_2



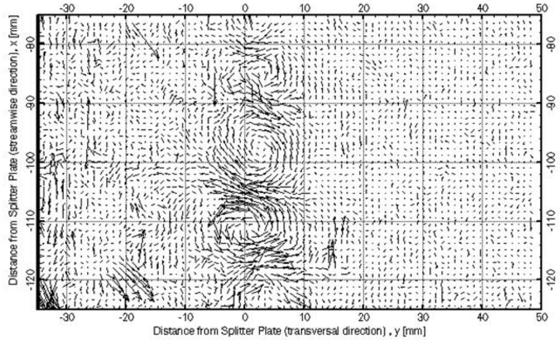
U_1 ▼ U_2







Instant. fluct. ($v'_{x;}v'_y$)



(transversal $T.I._y$)