EXPERIMENTAL CHARACTERIZATION OF AN AIR/SF6 TURBULENT MIXING ZONE INDUCED BY THE RICHTMYER-MESHKOV INSTABILITY

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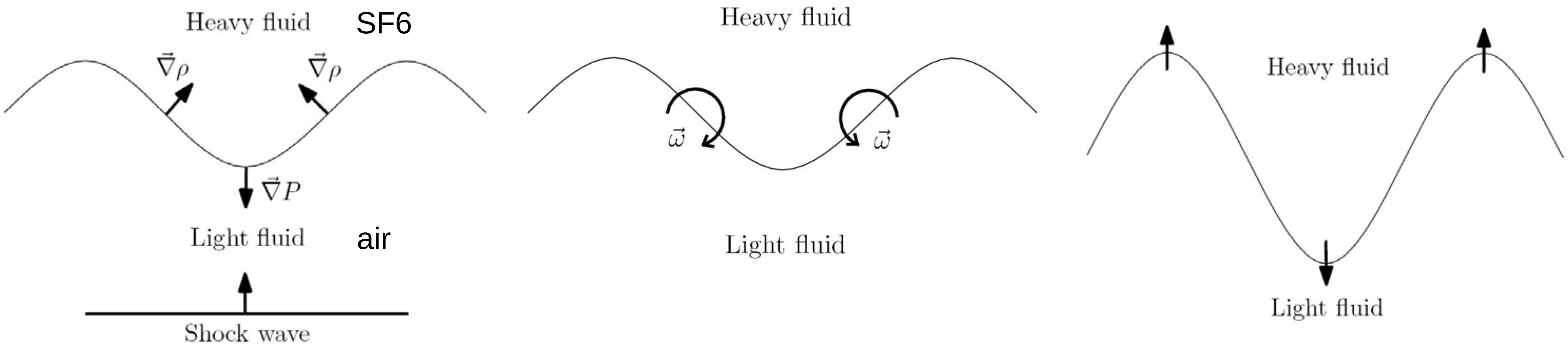
ISAE-CEA partnership on the study of turbulent gaseous mixing induced by the Richtmyer-Meshkov instability (RMI)

The RMI is a baroclinic instability :

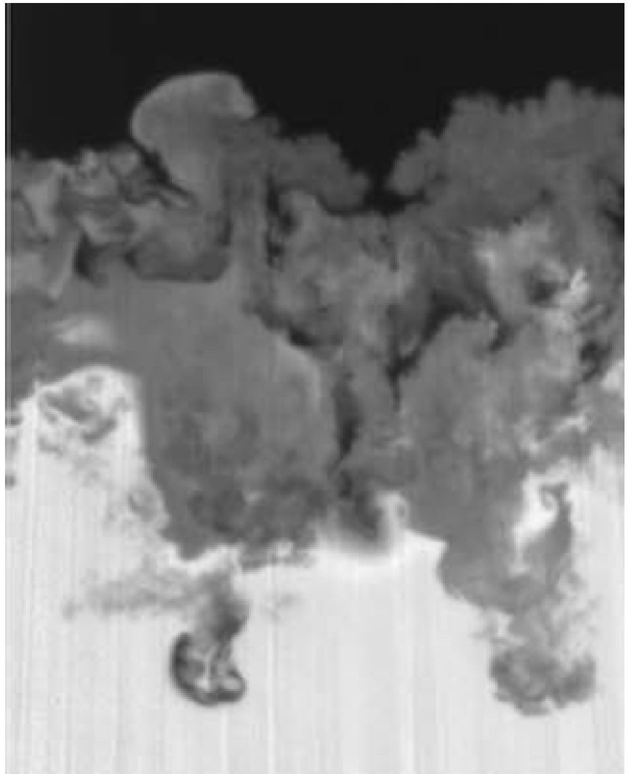


$$\frac{d\vec{\omega}}{dt} = \vec{\omega} \cdot \vec{\nabla}\,\vec{u} - \vec{\omega}\,\mathrm{div}\,\vec{u} + \frac{1}{\rho^2}\vec{\nabla}\rho \wedge \vec{\nabla}p + \nu\nabla^2\vec{\omega}$$

Non parallel density and pressure gradients

$\longrightarrow$ vorticity production $\longrightarrow$ turbulent mixing zone (TMZ)

Context of the work



Early development :
Mushroom shape
Jacobs & Krivets, PoF17, 2005

Late times :
Turbulent Mixing Zone (TMZ)
Weber et al., PoF24, 2012

ISAE-CEA partnership on a shock tube based study of TMZ induced by the RMI at the shock and re-shock phases

RMI and ensuing TMZ perturbate ICF (inertial confinement fusion) target implosion and are present in supernovae explosions and in supersonic combustion in ramjets.

→ Need of efficient predictive tools for RMI induced turbulence (partially validated by shock tube experiments at CEA: SF6-air Poggi et al. [Phys Fluids, 1998], air-SF6 Haas et al. [TMB Workshop, 2007], Mariani et al. [10th IWPCTM, 2006]).

→ Need of reference experimental data to validate those predictive tools in addition to TMZ growth rate.

→ Shock tube experiments at ISAE following those at CEA/DAM/DIF: flow visualization and velocity measurements.

Purpose of the work

→ Shock tube relocation from Bruyères near Paris to Toulouse and modernization

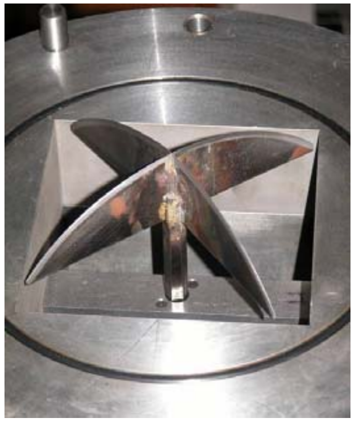
→ Measurement of the growth rate of the TMZ using time-resolved Schlieren visualizations. Previous work at CEA was performed with a still camera (one picture/run) for L_{SF6} = 250 and 300 mm. Image analysis.

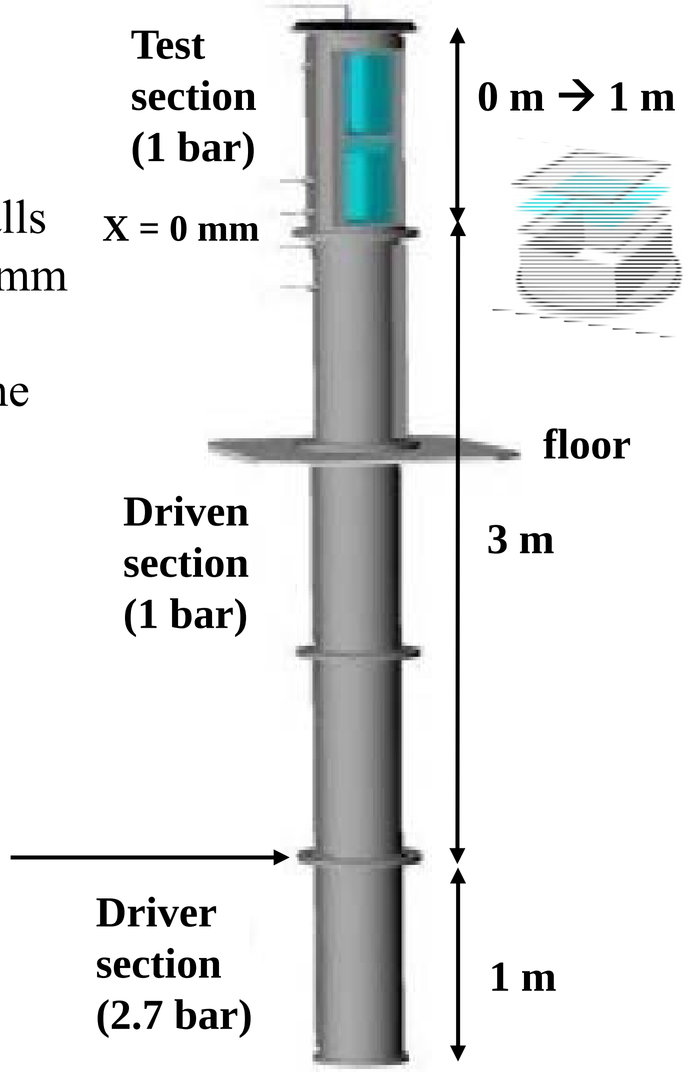
→ Characterization of the velocity evolution in the TMZ produced by the RMI using two-components Laser Doppler Velocimetry (LDV) to confirm and generalize previous measurements at CEA for L_{SF6} = 250 and 200 mm.

→ Investigation of new diagnostics : laser sheet tomography and time-resolved particle image velocimetry (TR-PIV).

Vertical shock tube on two levels

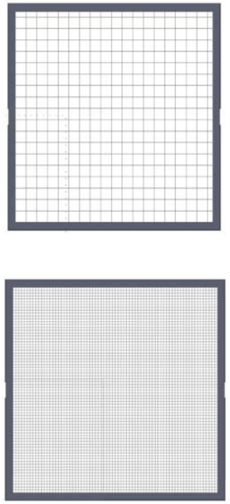
- 5 m long
- Square cross section : $(130\ \text{mm})^2$
- transparent test section on 4 side walls
- length of the test section $L_{SF6} = 250$ mm set by a movable end plate
- Blade cutting device used to break the membrane separating the driver and driven sections





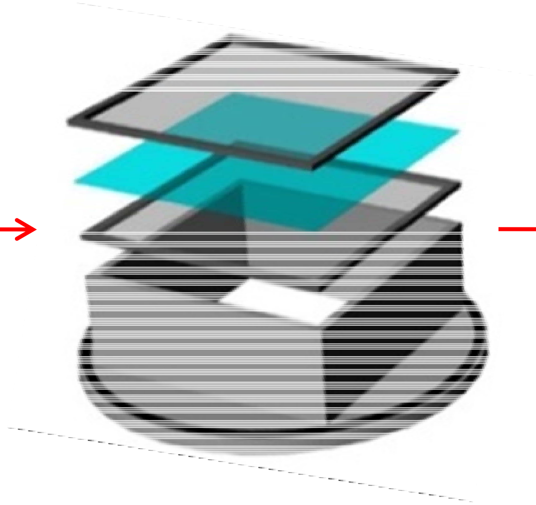
Scheme of the two grids –microfilm assembly used for the generation of the initial perturbation of the interface: wave length = upper grid spacing

Upper mesh spacing
=1.8mm

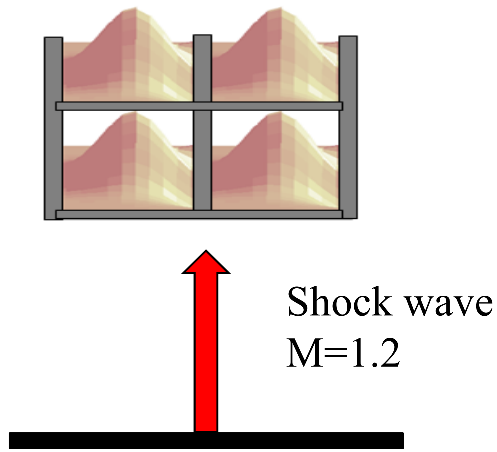


Lower mesh spacing
=1mm

Two wire grids



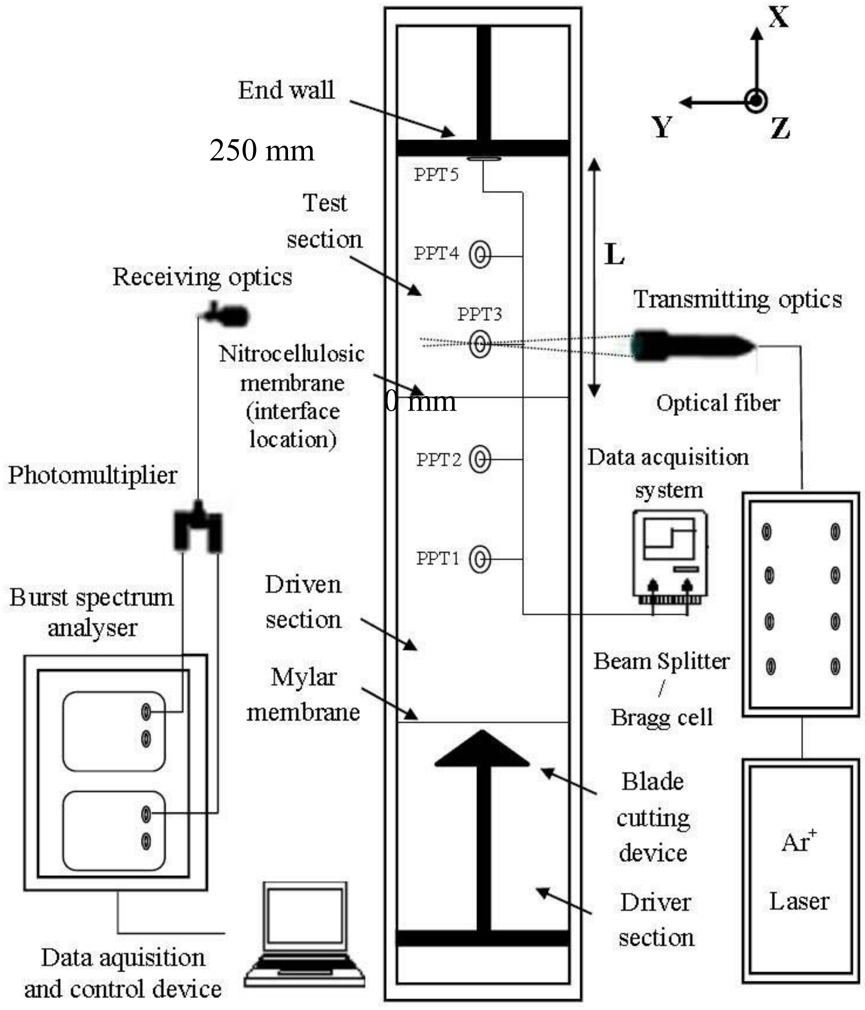
square
steel support



Three dimensional, sinusoïdal (egg crate) perturbation on the interface, with initial amplitude imposed by shock loading of microfilm

3 simultaneously acquired diagnostics

- **5 Pcb transducers** (f c.o.=500 kHz), 2 in driven section (air) at 115 and 315 mm, 3 in test section (SF6) at 43, 213 and 250 mm. Shock waves velocities and pressures
- **Time-resolved Schlieren visualizations** centered at two locations
  - High-speed Phantom V12 camera
  - Data rate of the image recording : 27000 frames per second
- **Laser Doppler Velocimetry (LDV)** with maximum data rate ≈ 450 kHz
  → U axial fluid velocity at 43, 135 and 150 mm above the initial position of the interface (grids)
  → V transversal velocity at 43 mm



Schematic set up, not to scale

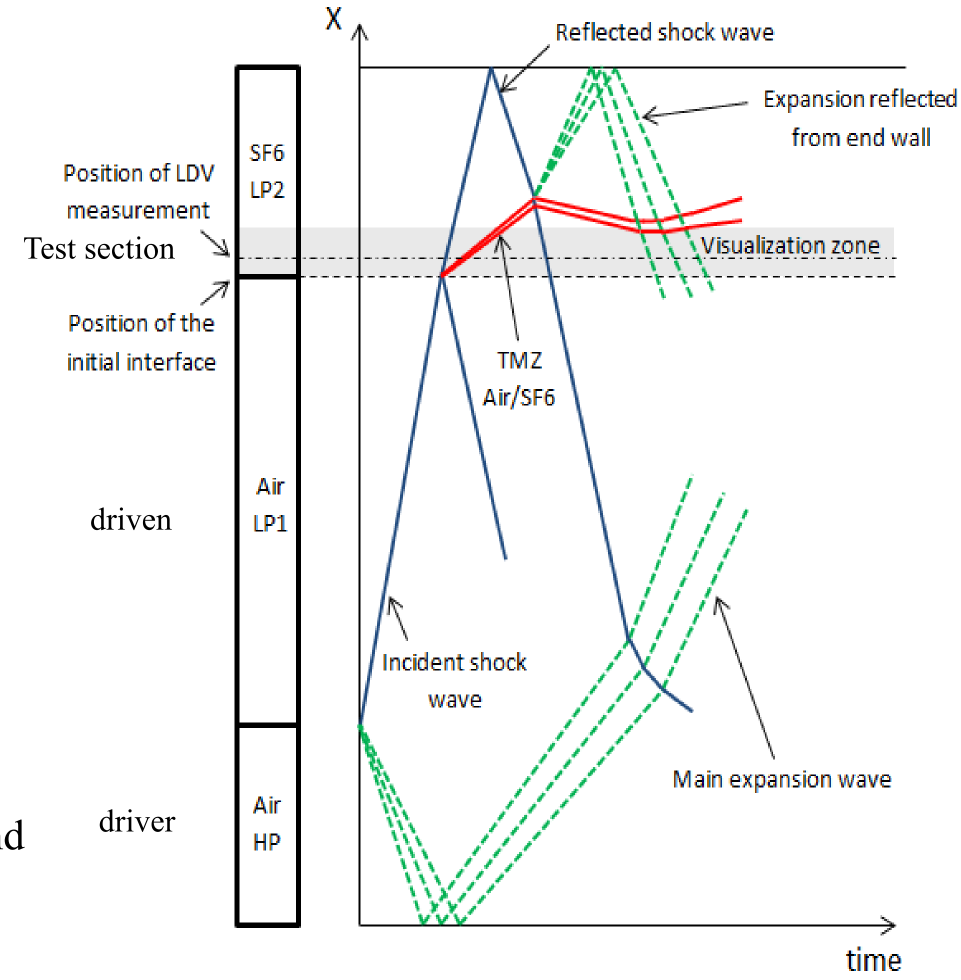
Wave diagram of air / SF6 mixing flow configuration

- Nitrocellulosic membrane

  (e ≈ 0.5 µm) trapped between 2 grids :

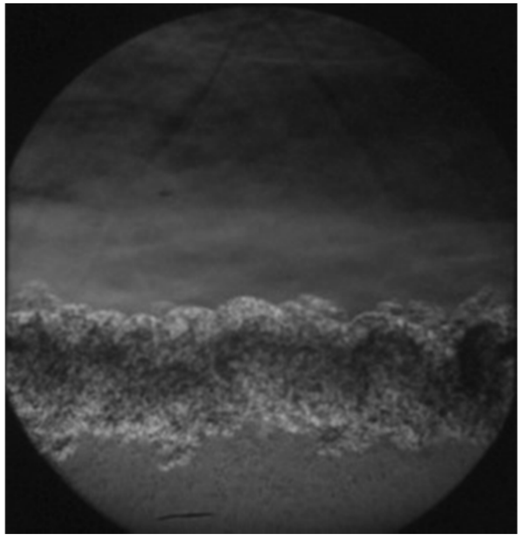
  - Upper mesh : 1.8 mm
  - Lower mesh : 1 mm

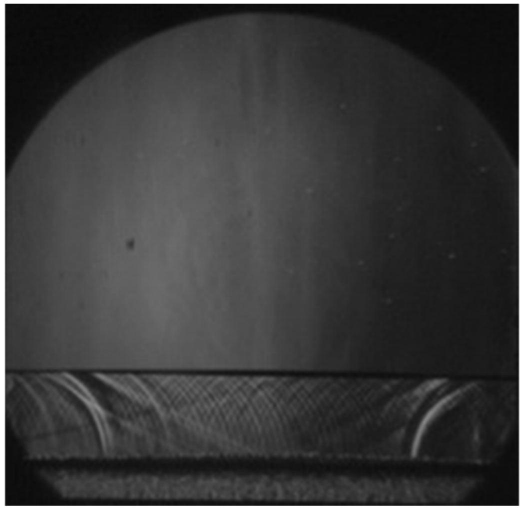
- Atwood number : 0.699
- Incident Mach number : 1.2
- L_{SF6} = 250 mm
- TMZ created by incident shock, excited by reflected shock first, rarefaction wave next and finally by the main expansion wave from the driver (as seen on movies).

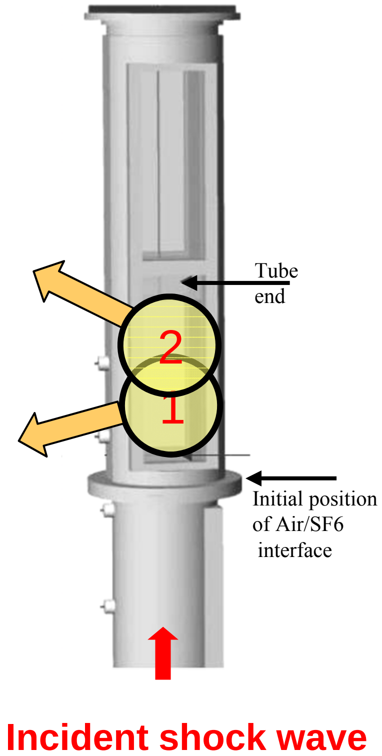


Air / SF6 mixing flow configuration

- Time resolved Schlieren visualization (movies at 2 locations)







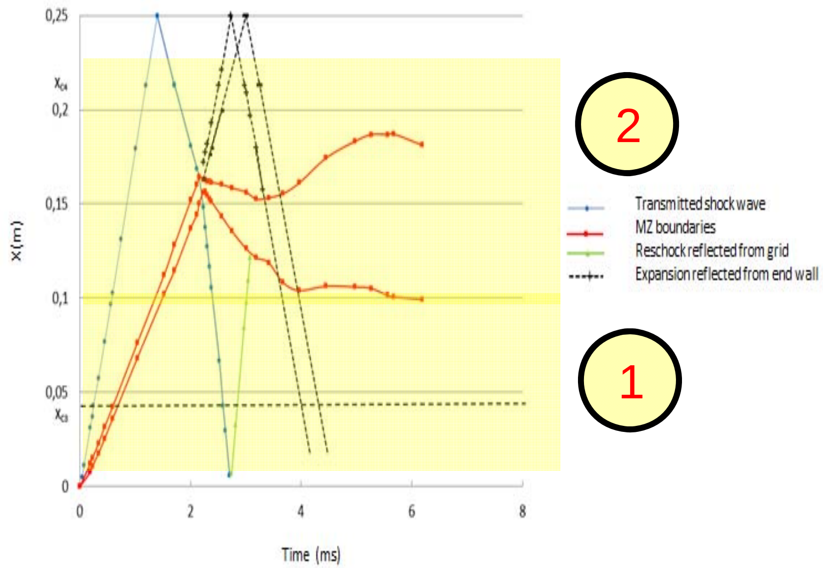
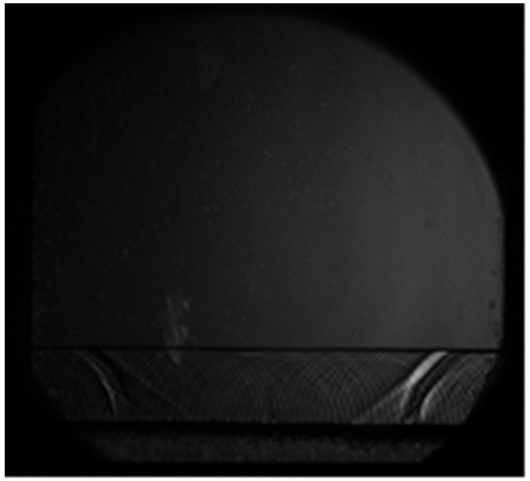
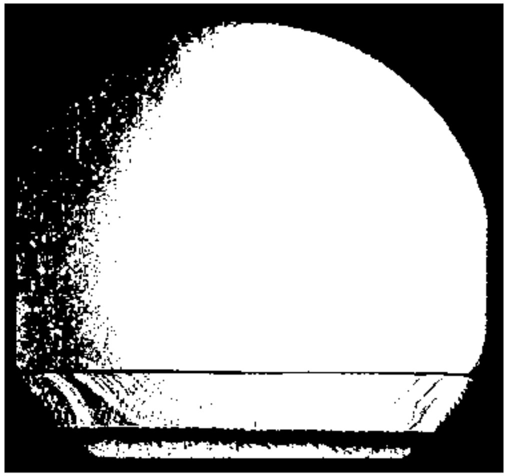


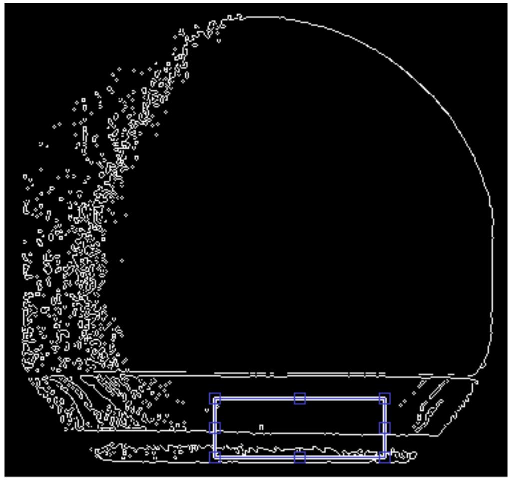
Image analysis using a spatial filter



Schlieren image

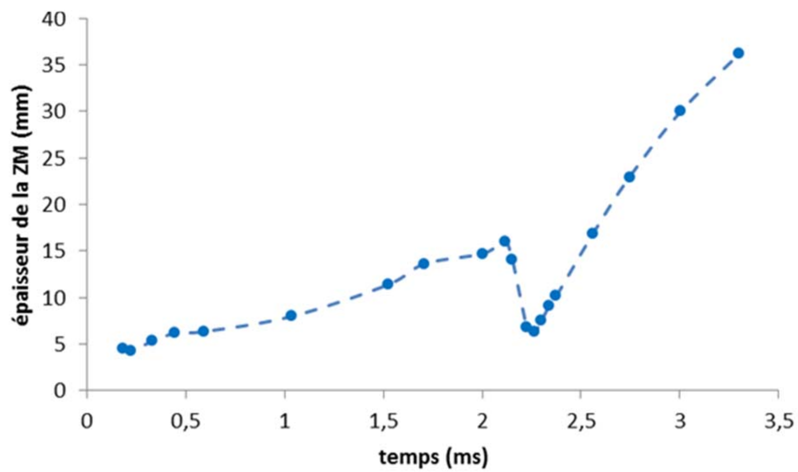


Output of Otsu's method



Region of interest (ROI)

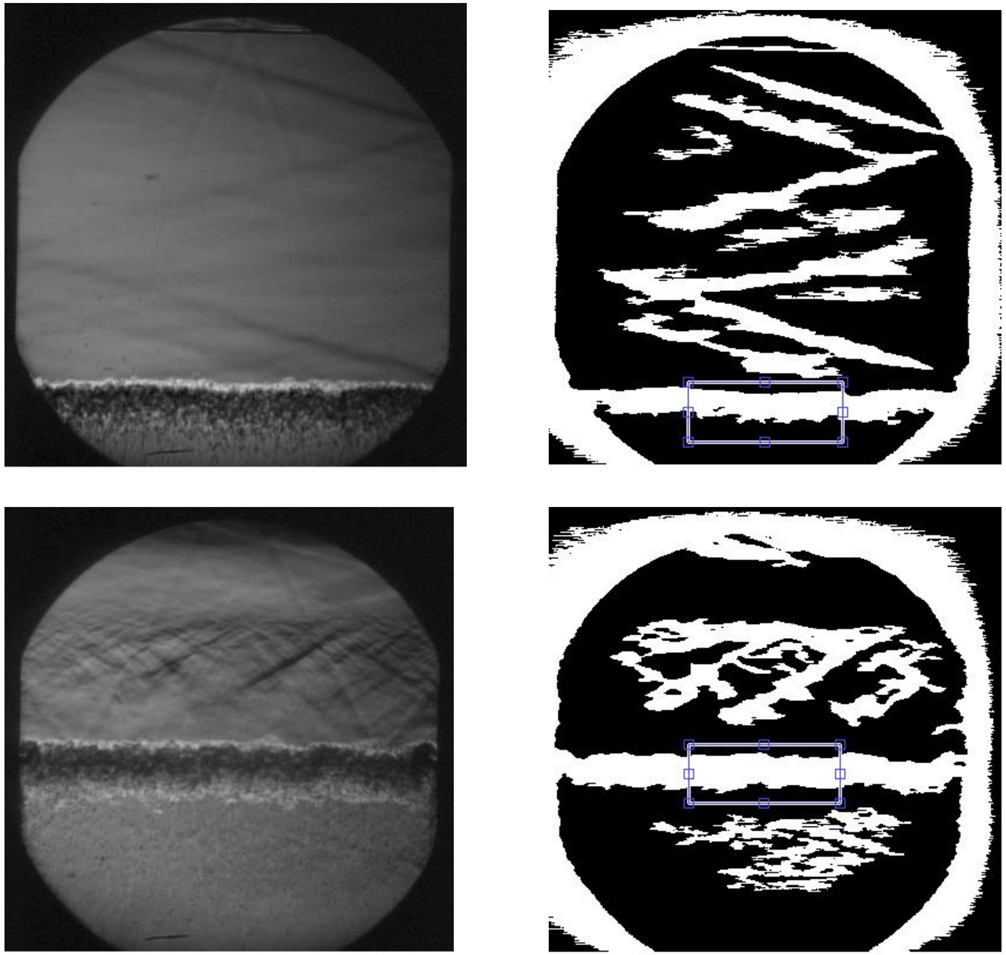
Measurement of the TMZ thickness vs. time.
Variations due to irregular boundaries detection on the Schlieren images.



Method 1 : High pass frequency filter directly on the original image

Before reshock

After reshock



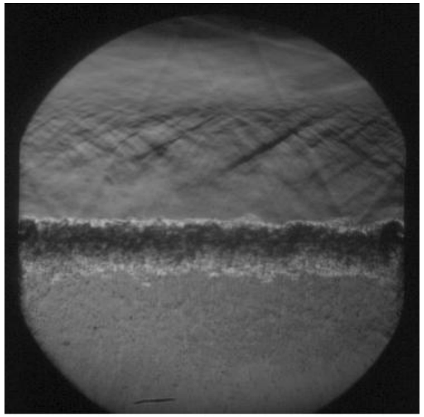
Schlieren image

Output of the filter

Only the dark band inside the TMZ is detected

Method 2 : High pass frequency filter applied on the image without the background

After reshock



Schlieren image

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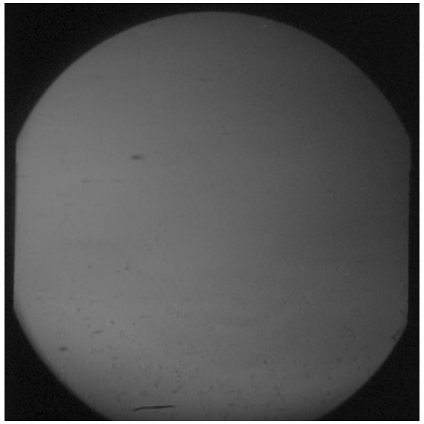
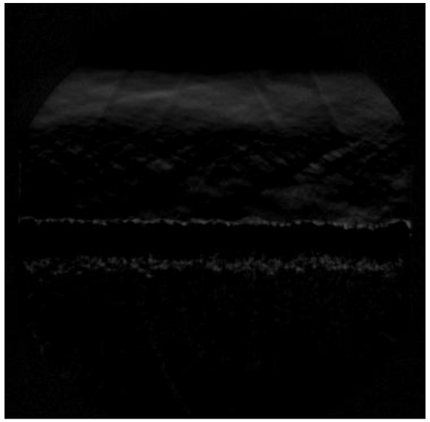
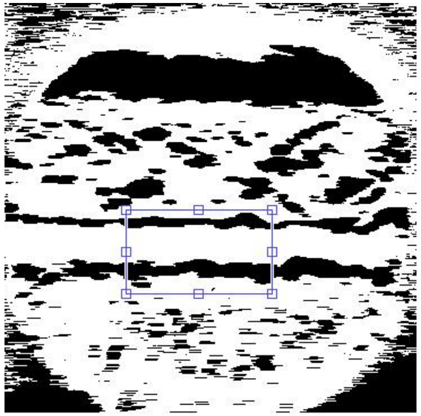


Background

=



« Substracted » image



Output of the filter

Detection close to what
is seen by the eye

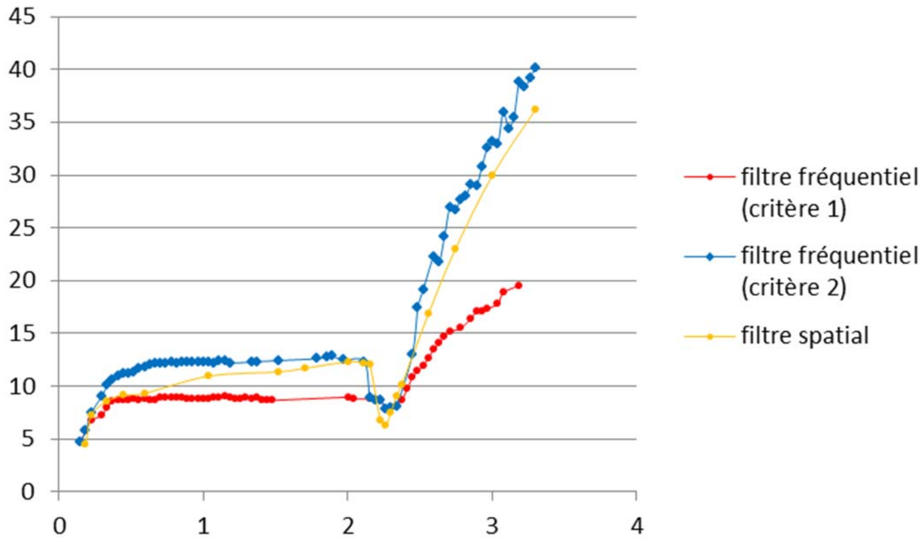
Still a lot of variability and arbitrary in the TMZ thickness

Effect of the microfilm fragments on the continuity of the TMZ boundaries ?

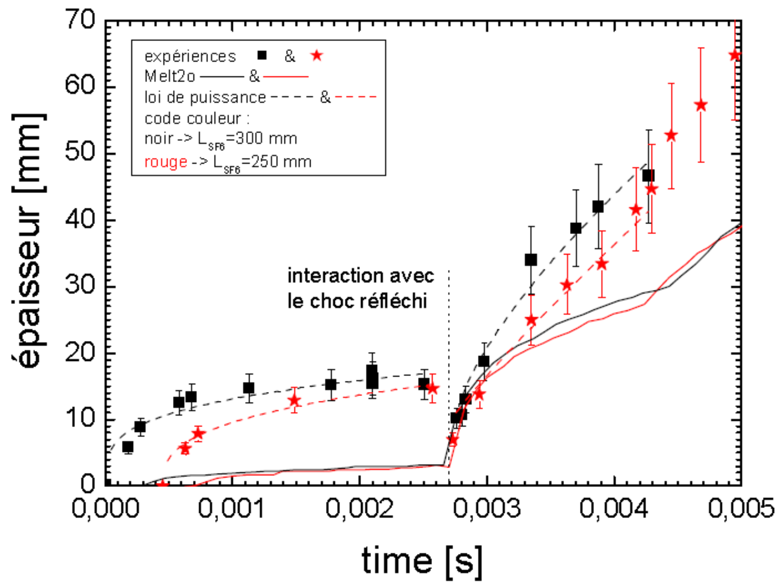
+

Wall effects on the Schlieren images ?

- discontinuity of boundaries better seen after reshock
- Difficult to clearly determine the real TMZ thickness (as in CEA)



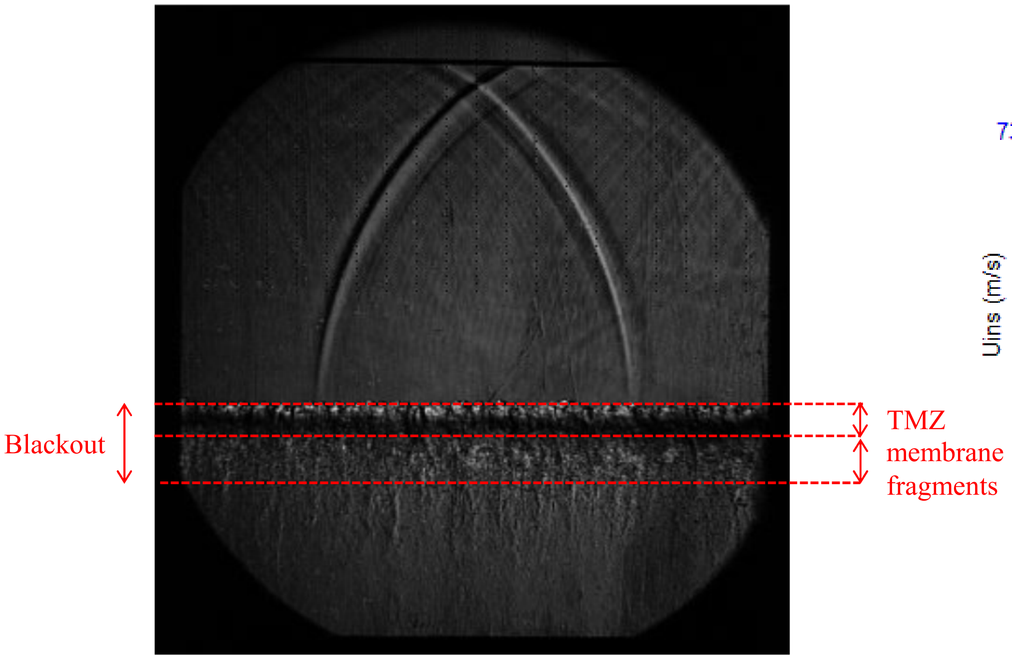
ISAE results, 250 mm, 2 methods

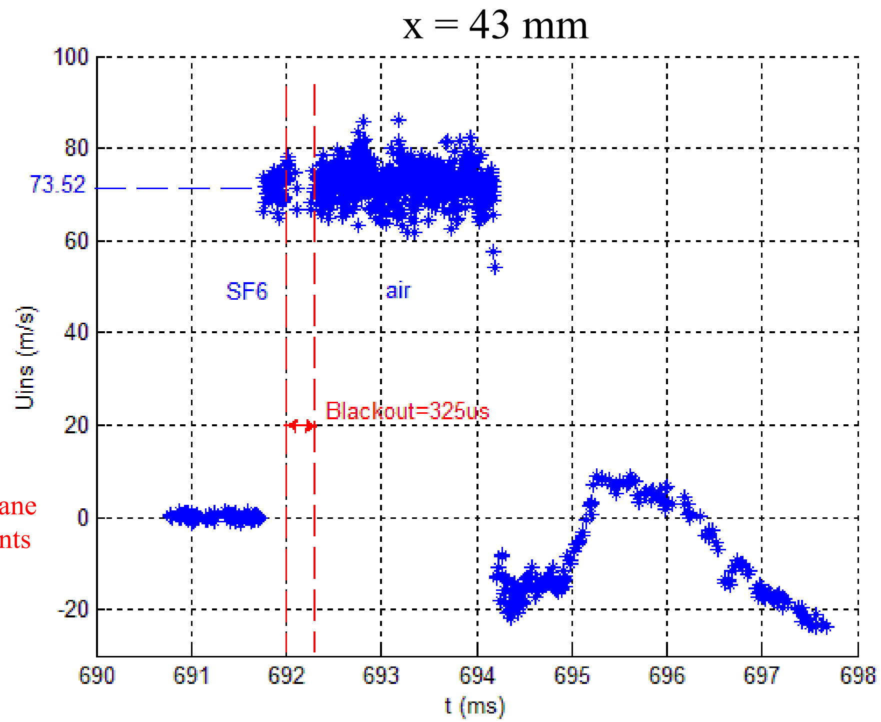


CEA results (IWPCTM 10, 2006) 250 and 300 mm

Time evolution of the instantaneous longitudinal velocity

- The SF6-transmitted shock wave accelerates the flow to 73.5 m/s.
- 325 µs long black-out in the velocity plateau
- The thickness of the TMZ based on Schlieren images is 7 mm
  - The crossing of the TMZ through the measurement volume lasts 95µs
  - The membrane fragments still hinder the LDV measurement volume 230 µs after the passage of the TMZ



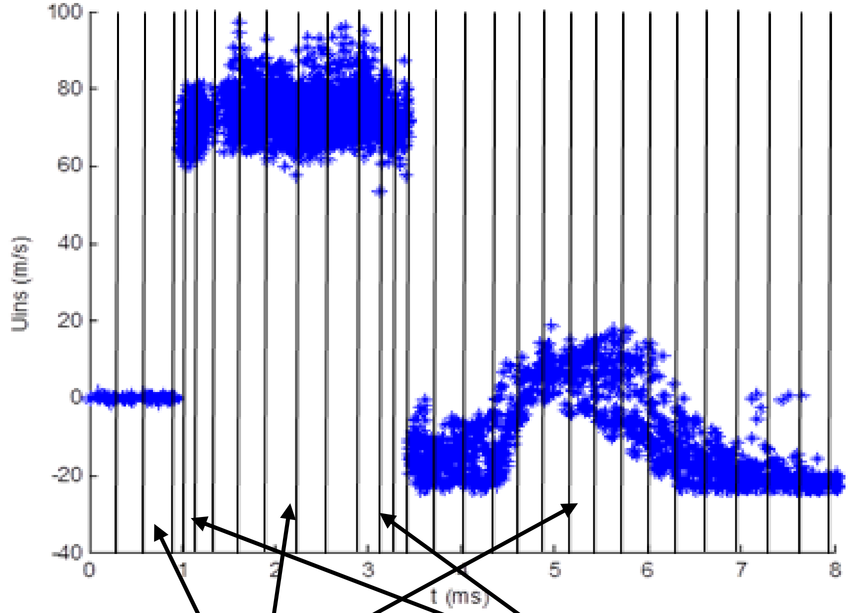


Time origin : start of LDV data acquisition

Superposition of longitudinal velocities

- Phase-averaging performed on the velocity signals obtained with 35 shots
- Time discretization of the superimposed signals

Time origin : shock interface interaction

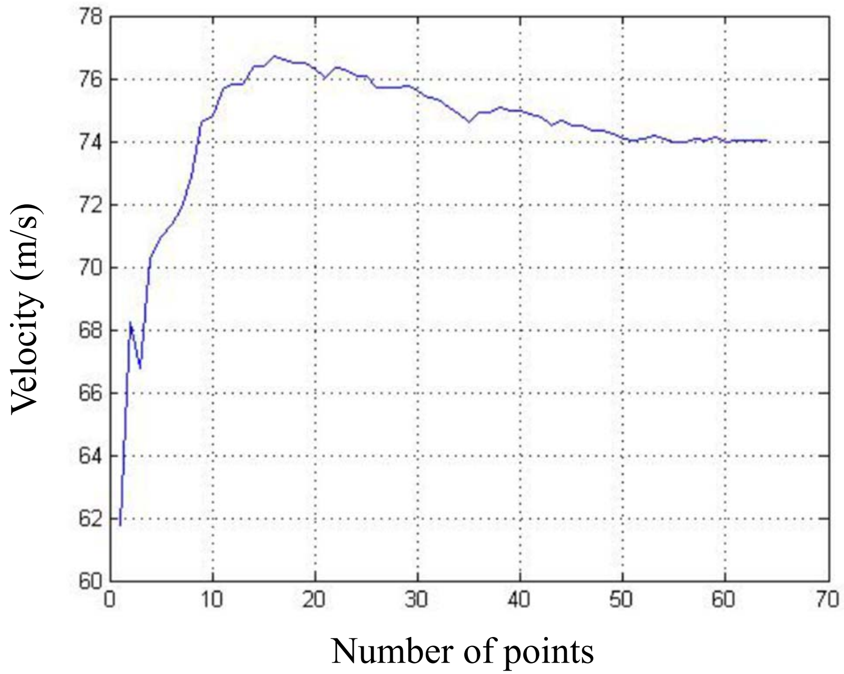


Δt = 40 μs   Δt = 10 μs

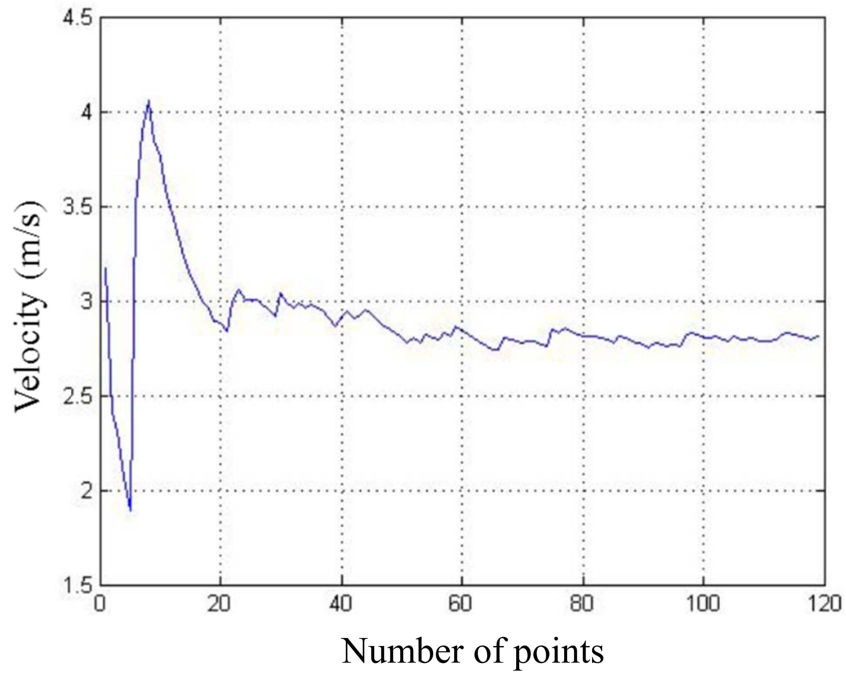
- Convergence reached with 100 samples in each time window

Convergence analysis for longitudinal velocity

Statistical convergence reached on the plateau duration between shock and reshock with a number of points per sampling window (40 µs and 10 µs during transients at wave passages) equal to 100, but good enough with 50 points.



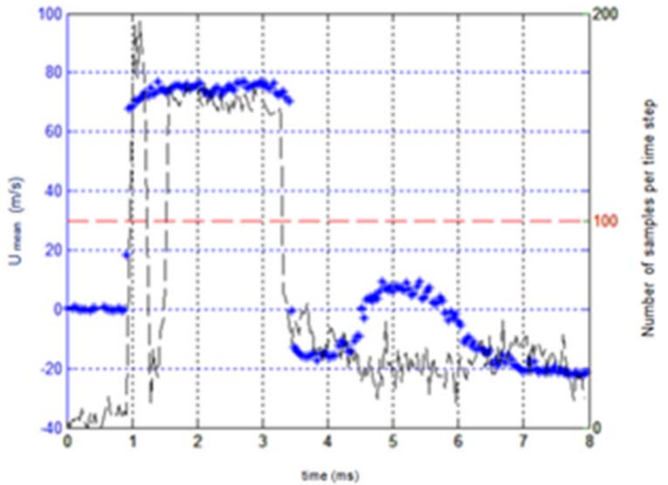
First order convergence (on the mean velocity) : good with 50 points

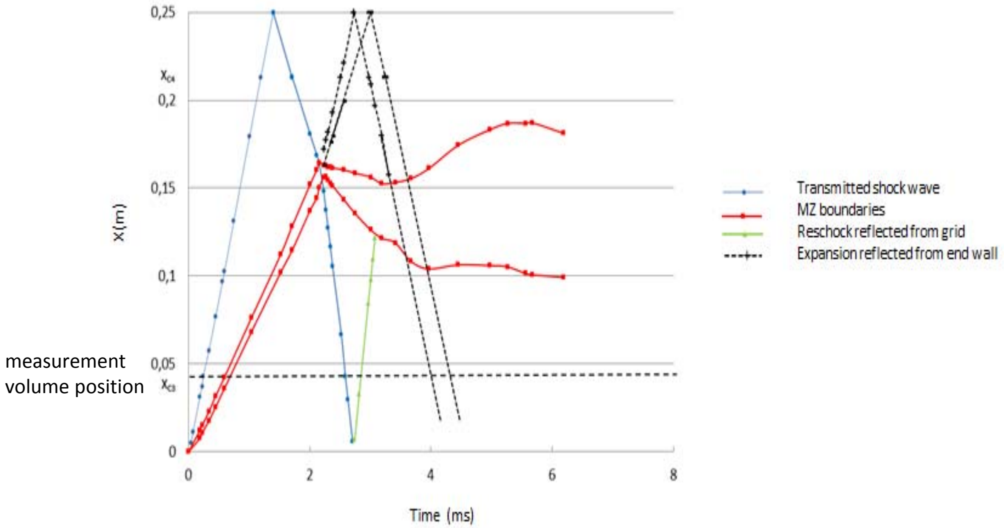


Second order convergence (on the velocity rms) : good with 50 points

Mean longitudinal velocity at 43 mm

- Mean velocity (m/s) obtained from 35 shots (blue points)





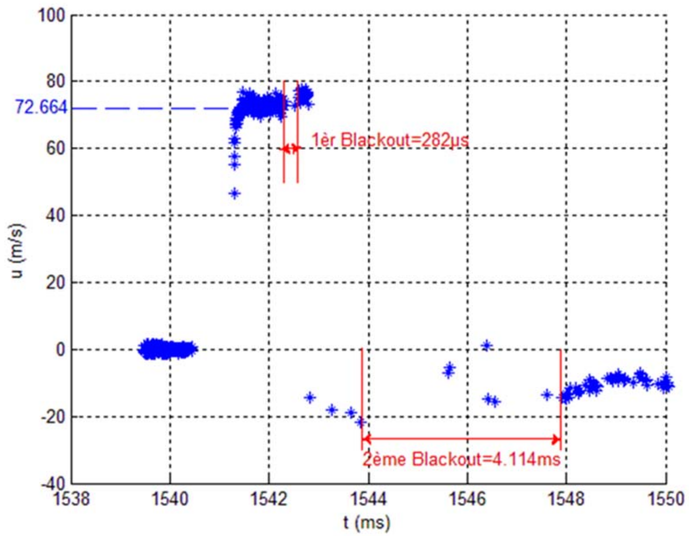
- Thin broken line : convergence reached only in the plateau located between the transmitted and reflected shocks except inside the blackout (not a problem for the evaluation of the mean velocity)
- The gases are first accelerated to 73.5 m/s (at t_1=0.95 ms) then slow down to -18 m/s (at t_2=3.4 ms). They are accelerated once again to 5 m/s (t_3=4.64ms)

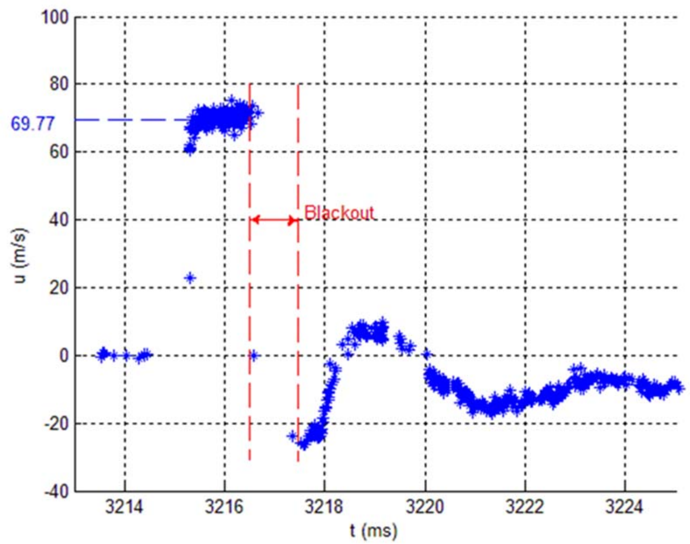
Instantaneous velocities at 135 and 150 mm

The shock wave transmitted in SF6 accelerates the gases to 73 m/s and 70 m/s for measuring stations x=135 mm and x=150 mm respectively.

For x=135mm (same abscissa explored at CEA, presented at IWPCTM10, 2006), many microfilm fragments remain behind the TMZ leading to a **long black-out** and a low acquisition rate for LDV after reshock. The measuring station is below the center of the stagnating TMZ.

For x=150mm (right), the acquisition rate is improved (less fragments ?). The measuring station is above the center of the stagnating TMZ.



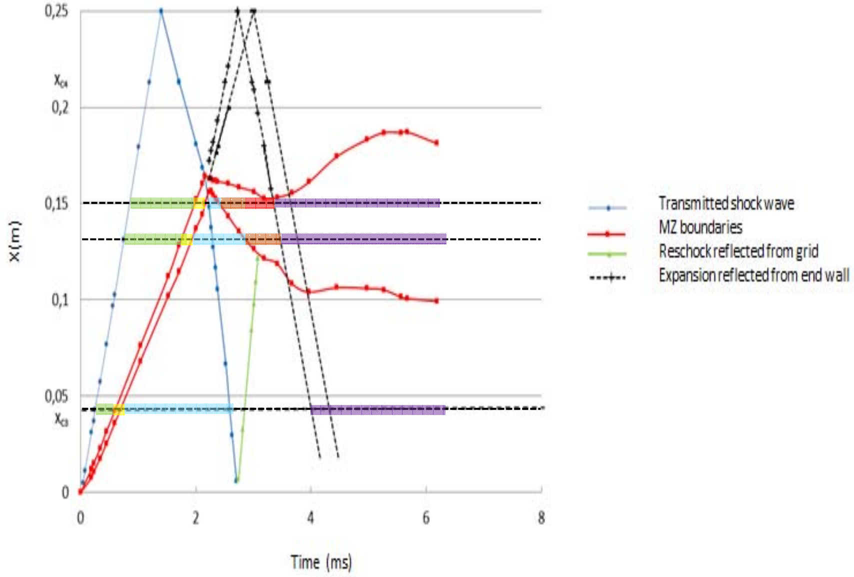


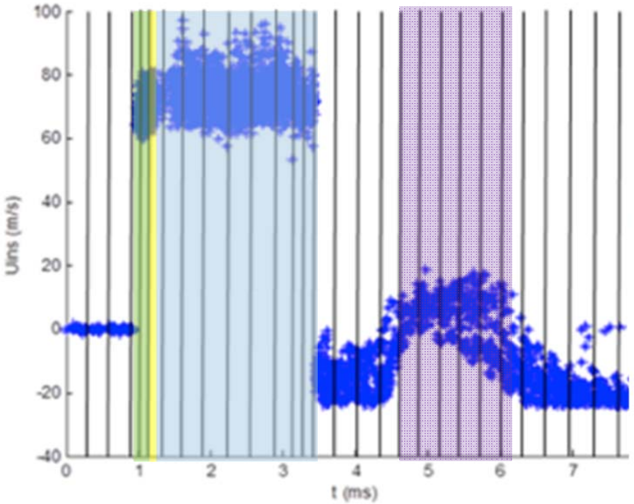
135 mm time origin: start of LDV data acquisition 150 mm

Phase averaged longitudinal velocities at 3 locations

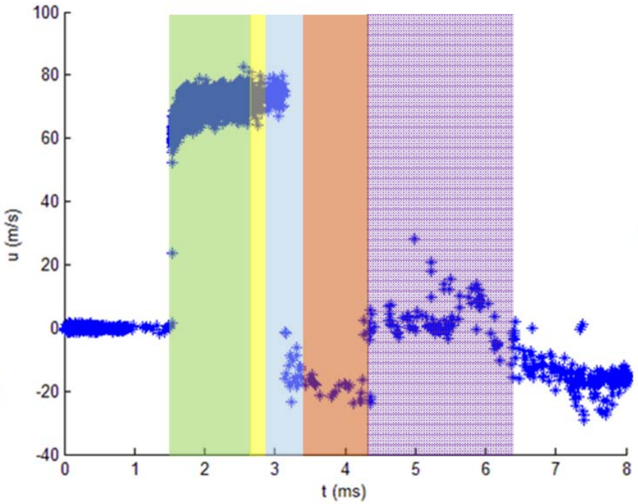
35 identical runs for x=43mm and135mm

44 identical runs for x=150mm

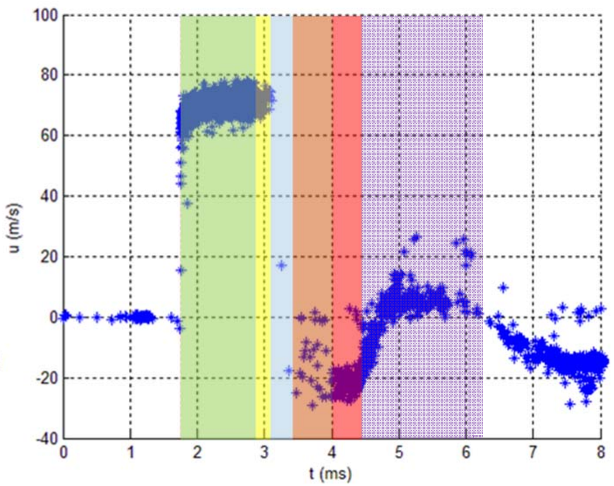




43 mm



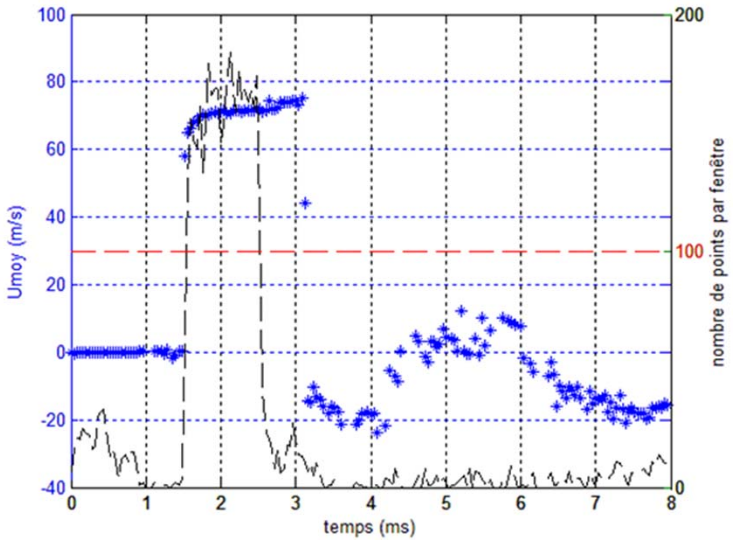
135 mm



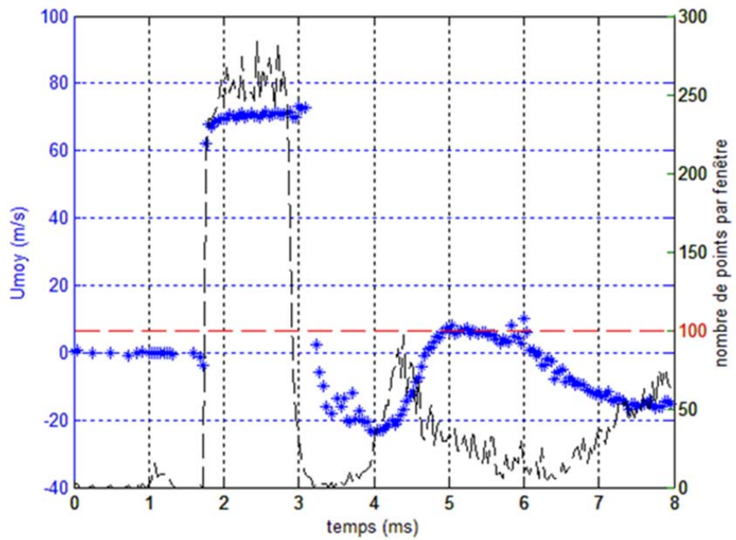
150 mm

Average longitudinal velocities

x = 135 mm



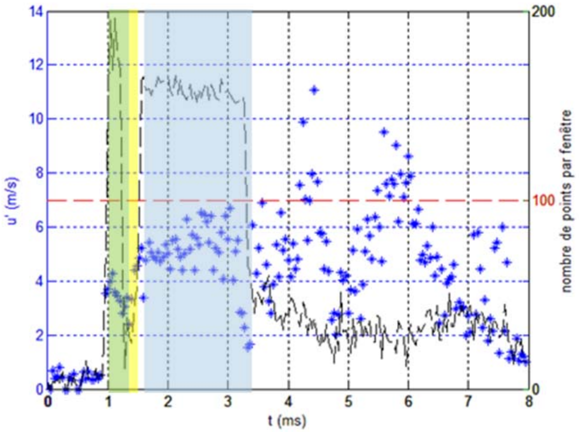
x = 150 mm



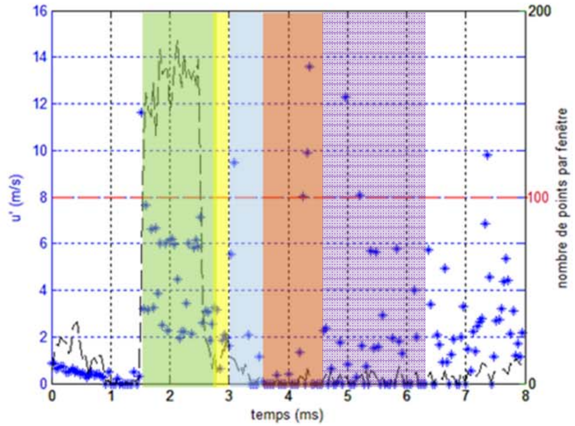
- For x=135mm the transmitted shock accelerates the gases (t=1,546ms) to 72 m/s, the re-shock at 3,15 ms slows them to [–21 m/s, –15 m/s] and the rarefaction re-accelerates them to [0 m/s,10 m/s] starting at 4,35 ms.
- For x=150mm the transmitted shock accelerates the gases (t=1,765ms) to 70 m/s, the re-shock at 3,26 ms slows them to [–24 m/s, –15 m/s] and the rarefaction re-accelerates them [0 m/s,7 m/s] starting at 4,25 ms.

Longitudinal velocity rms (& turbulence intensity)

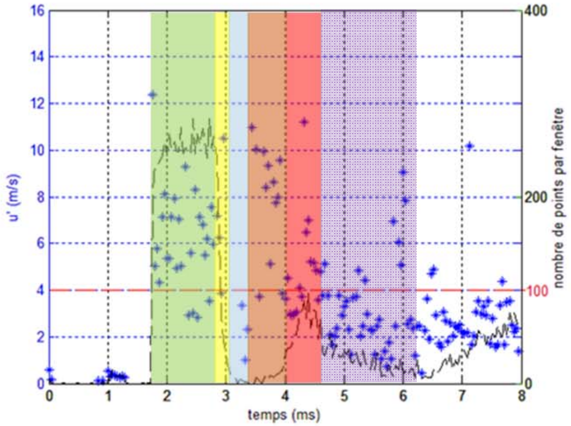
x = 43 mm



x = 135 mm



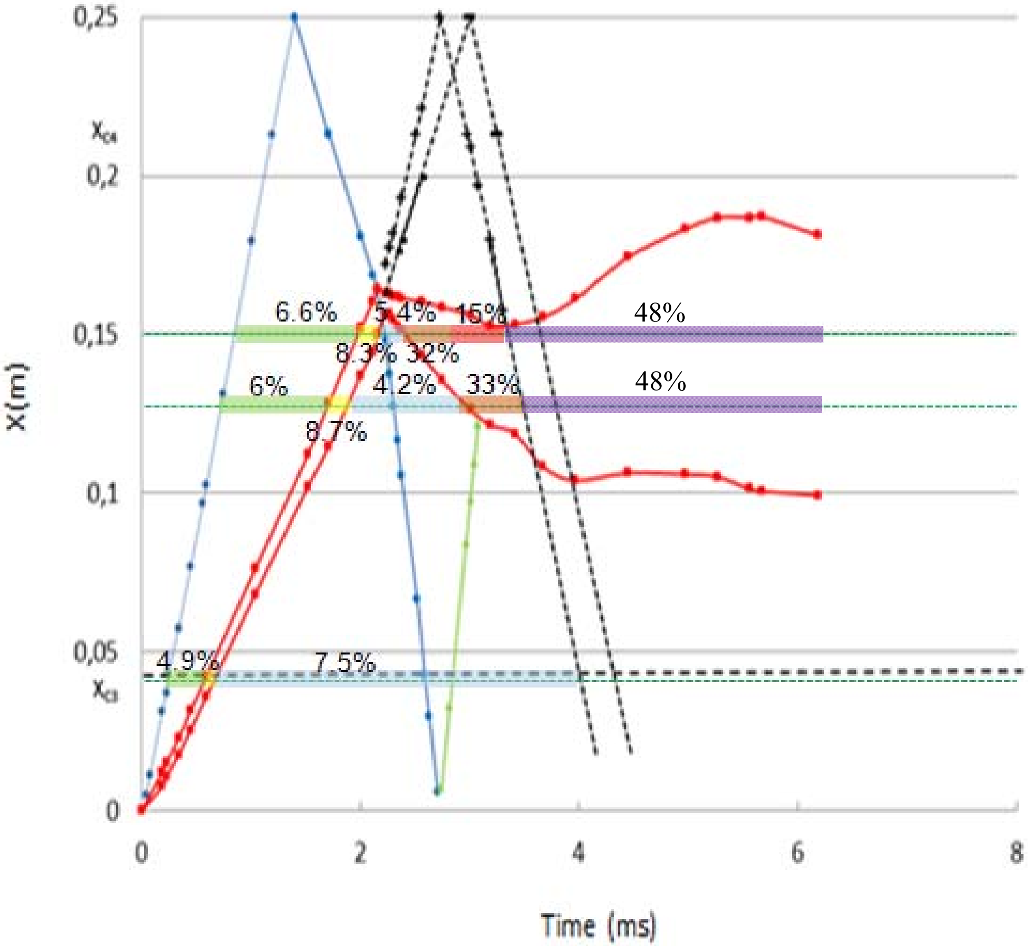
x = 150 mm



	X=43mm	X=135mm	X=150mm
Zone A	3,63 m/s (4,9%)	4,26 m/s (6%)	5,05 m/s (6,6%)
Zone B	-----------	6,24 m/s (8,7%)	5,976 m/s (8,3%)
Zone C	5,33 m/s (7,5%)	3,05 m/s (4,2%)	3,7 m/s (5,4%)
Zone D	-----------	5,2 m/s (33%)	7,46 m/s (32%)
Zone D'	-----------	-----------	3,45 m/s (15%)
Zone E	5.63m/s (57%)	2,95m/s (48%)	2.68m/s (48%)

After reshock low level of velocity rms but high turbulent intensity because mean velocity is low.

Longitudinal fluctuating velocity/mean velocity (%) : summary



Summary and next investigations

- Specific image processing is used in order to detect mixing boundaries and quantify the growth rate of the TMZ before the impact of the reshock wave on the TMZ (spatial segmentation edge method and use of a high-pass frequency filter).
- Velocity mean and rms converged with 50 - 100 samples in the time discretization windows of the superposed signals in the plateau between shock and reshock except inside the blackout caused by microfilm fragments.
- Measurement of the turbulence levels in air/SF6 configuration before and after the passage of the reflected shock and rarefaction waves. Microfilm fragments create less black-out for 150 mm than for 135 mm and 43 mm.

Next investigations

- Measurement of TMZ thickness evolution for L_{SF6} = 100, 150, 200, 300 mm.
- Laser based tomography.
- Time resolved particle image velocimetry (TR PIV).
- Comparison with results from 3D code TRICLADE (CEA)