

Overpressure measurements by Triature PDV

Sébastien Maqueda^{a,b}, Julien Perchoux^a, Maylis Lavayssière^b and Yohan Barbarin^b

^a Université de Toulouse, LAAS-CNRS, CNRS, INPT, 31000 Toulouse, France

^b CEA-DAM, GRAMAT, F-46500 Gramat, France



Context : air overpressure measurement

At CEA Gramat research center, shock waves are characterized in open field detonation experiments

Need to develop faster pressure sensors than commercial ones

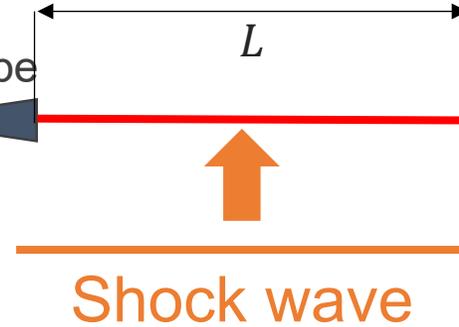
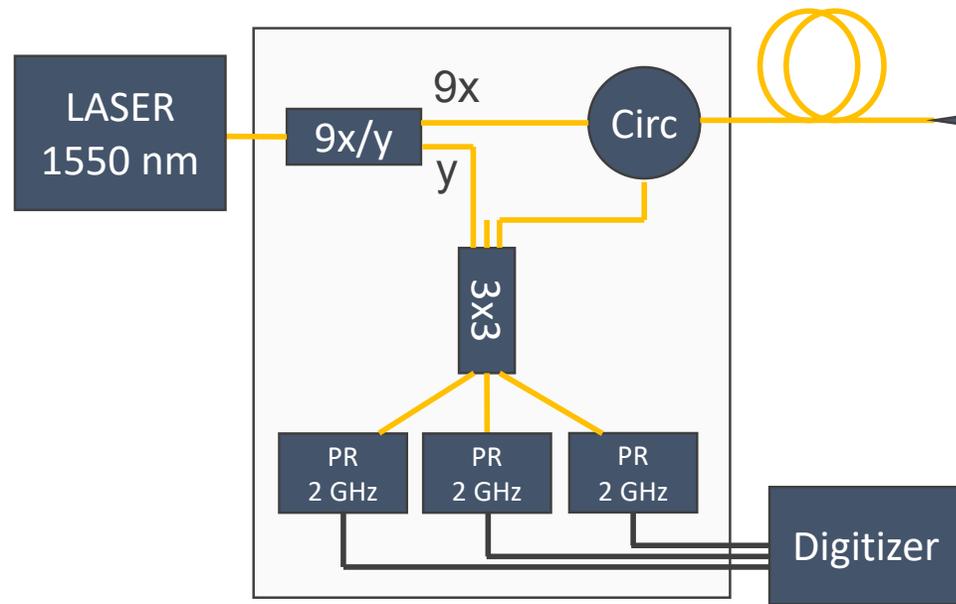
- Pressure range : [0 to 20] bar (at least)
- Bandwidth > 10 MHz

Optical sensors present potential advantages in dynamic pressure measurements

- Higher bandwidth
- Long distance signal communication
- Immunity to electromagnetic interferences



All-fiber PDV Triature



$L = \text{Constant}$

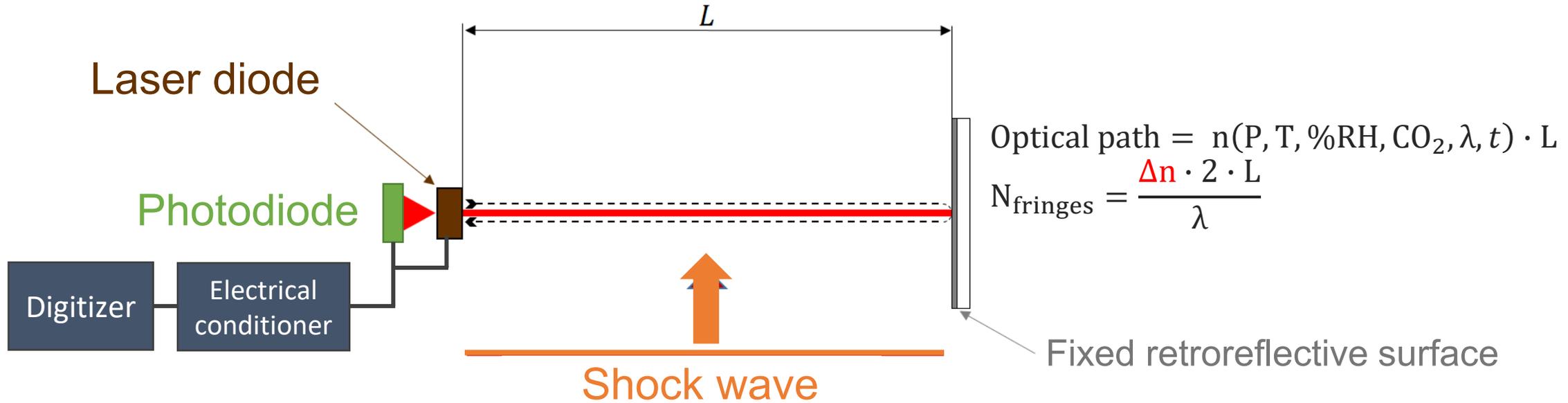
$$\Delta n = \frac{\lambda}{2 \cdot L} \cdot \frac{1}{2\pi} \cdot \arctan\left(\frac{S'_2(t)}{S'_1(t) + 2}\right)$$

$\lambda = 1550 \text{ nm}$

Fixed retroreflective surface

- Fiber-interferometer with 3 outputs shifted by $\frac{2\pi}{3}$
- Measurement of the refractive index variation induced by the shock wave along the laser beam, resolution about 10^{-8}
- Phase analysis signal processing (Triature), usually used for small displacement measurements
- Bandwidth $\approx 2 \text{ GHz}$

Initial approach : Self-Mixing Interferometer (SMI)



- 1 laser diode with a fixed reflector + 1 integrated photodiode (no fiber)
- Measurement of the refractive index variation induced by the shock wave along the laser beam
 - It depends on pressure, temperature and wavelength
 - Refractive index resolution of $1.9 \cdot 10^{-5}$
- Signal processing by interference fringe counting
- Very tolerant to alignment
- Bandwidth ≈ 20 MHz

Acousto-optic model



Rankine-Hugoniot equation gives the air overpressure $\Delta P(\rho)$ for shock waves

$$\Delta P = \frac{2 \cdot \gamma \cdot P_0 \left(\frac{\rho}{\rho_0} - 1 \right)}{\gamma + 1 - \frac{\rho}{\rho_0} (\gamma - 1)}$$

Current model valid up to 20 bar

$\Delta P = P - P_0$: air overpressure

ρ : density (g/cm^3)

γ : gas's specific coefficient

Gladstone-Dale law :

$$\rho = \frac{n - 1}{k}$$

$n = n_0 + \Delta n$: refractive index

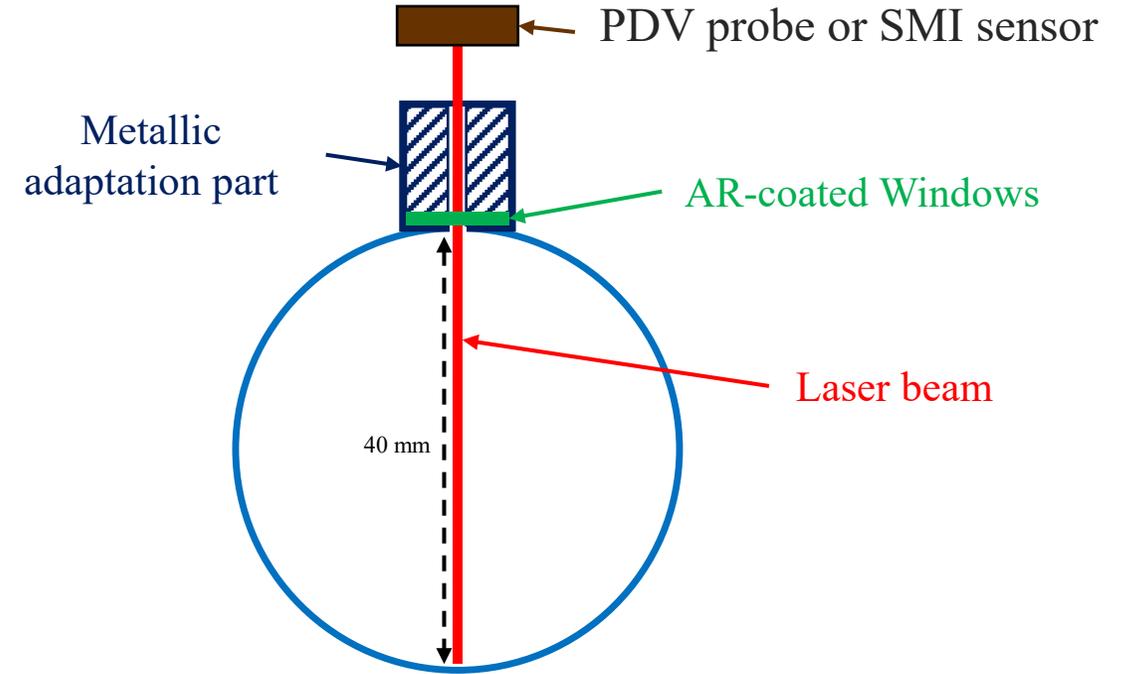
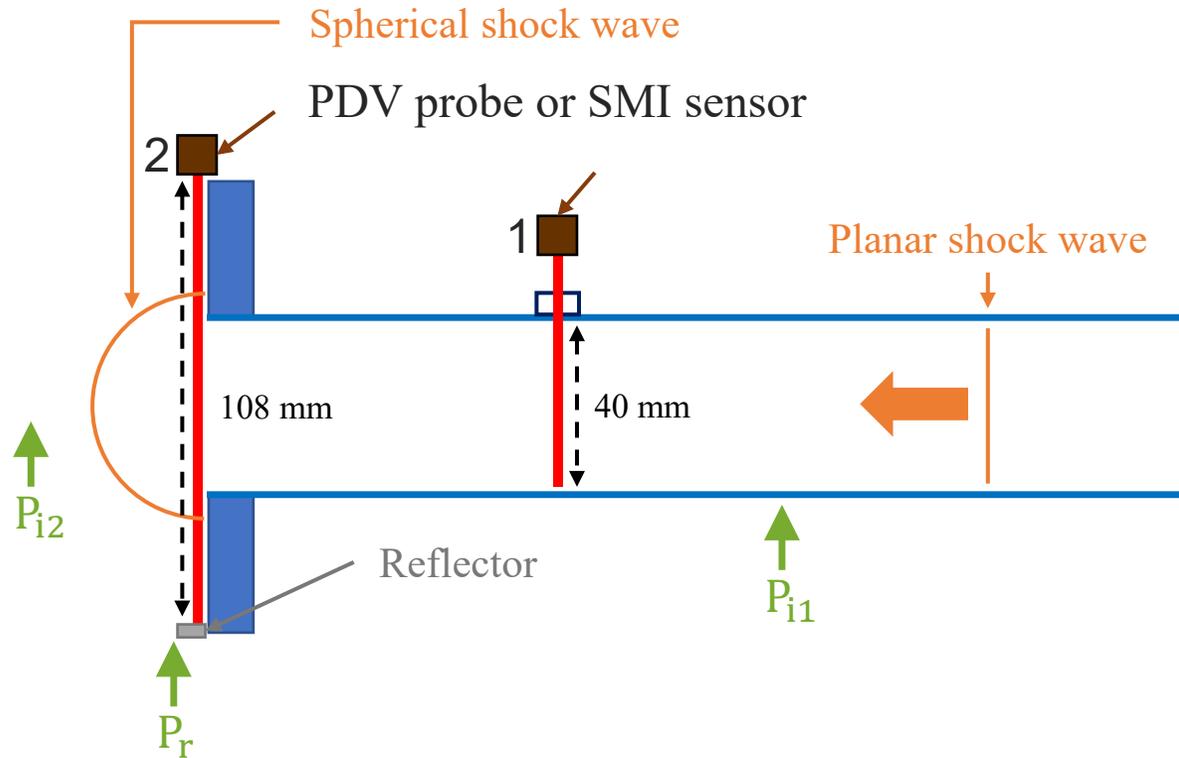
k : Gladstone-Dale coefficient (cm^3/g)

1st pressure step (« P_2 » in shock tube)

$$P_2 = P_0 + \frac{2 \cdot \gamma \cdot P_0 \left(\frac{R \cdot T_0 (n_0 + \delta n_2 - 1)}{M \cdot P_0 \cdot k} - 1 \right)}{\gamma + 1 - \frac{R \cdot T_0 (n_0 + \delta n_2 - 1)}{M \cdot P_0 \cdot k} (\gamma - 1)}$$

✓ Validated with SMI experiments

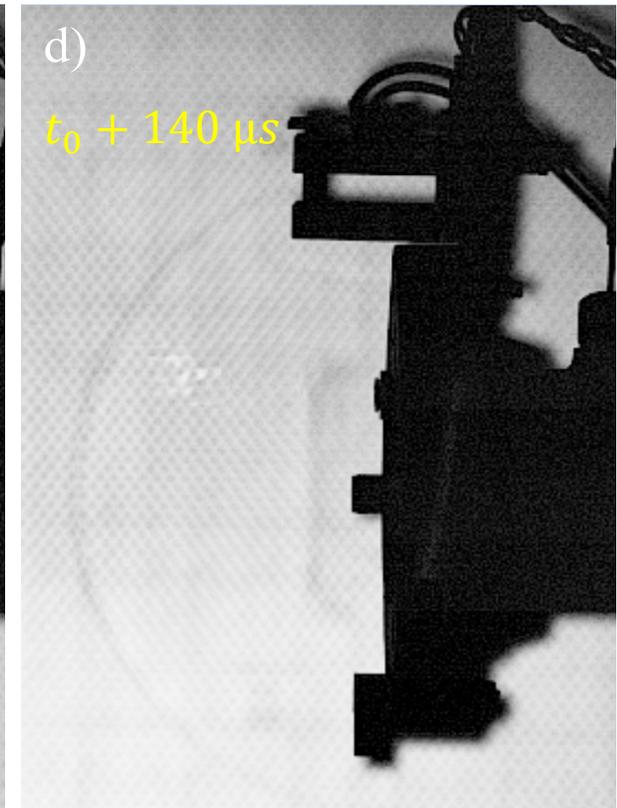
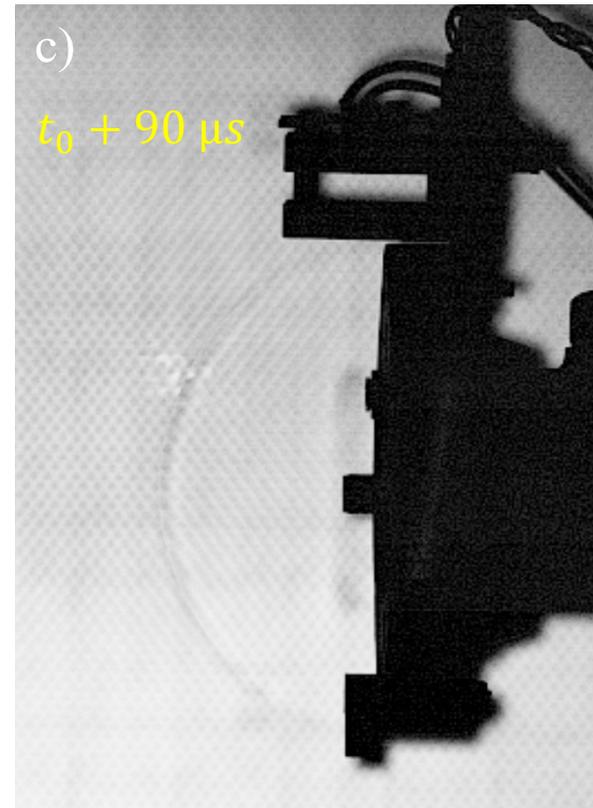
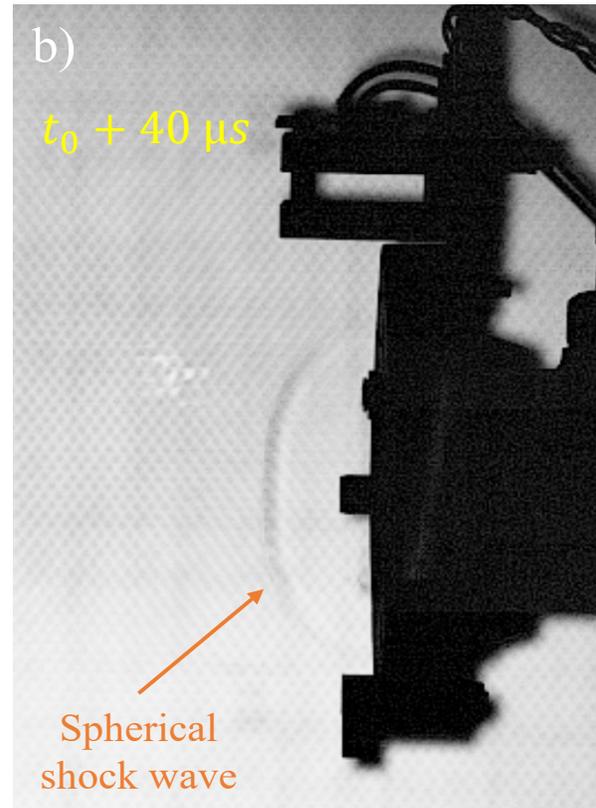
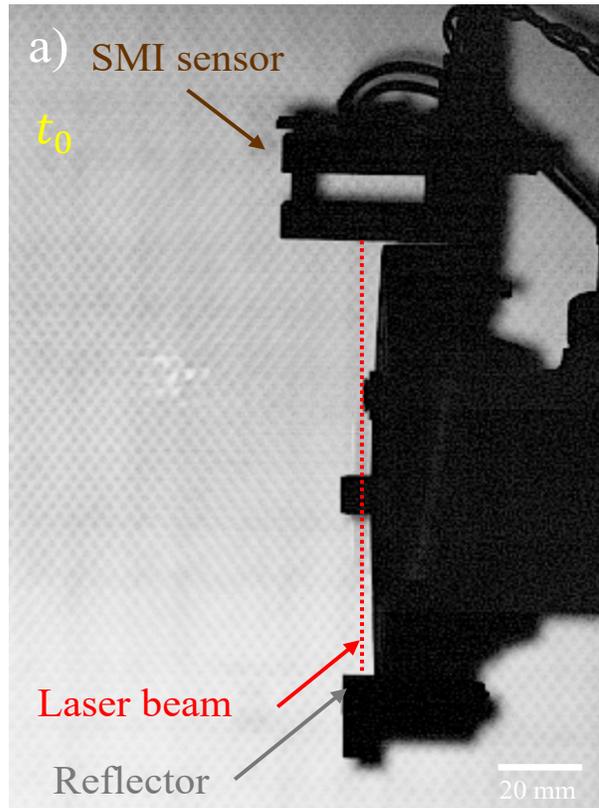
Open shock tube setup



- Metrological open shock tube with an inner diameter of 40 mm
- Incident pressure measurement (1) → planar shock wave
- Exit pressure measurement (2) → spherical shock wave

- Air gas in driver section
- $P_{i1} \approx 1.43$ bar (measured)
- Sampling rate of 20 GSa/s

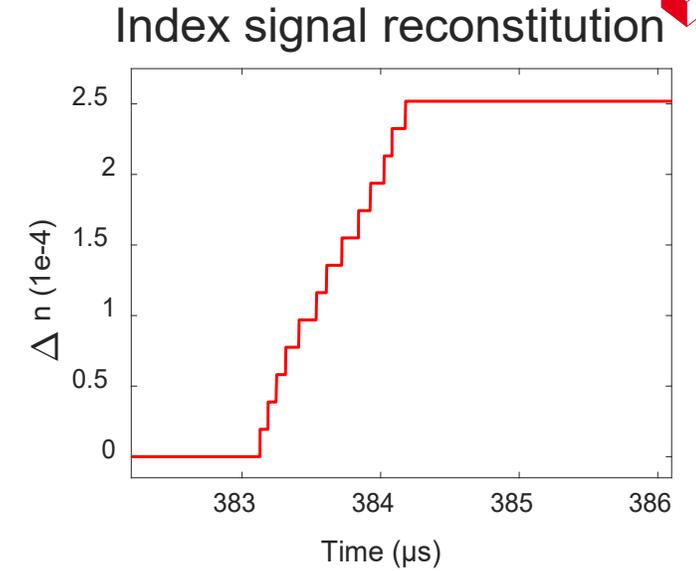
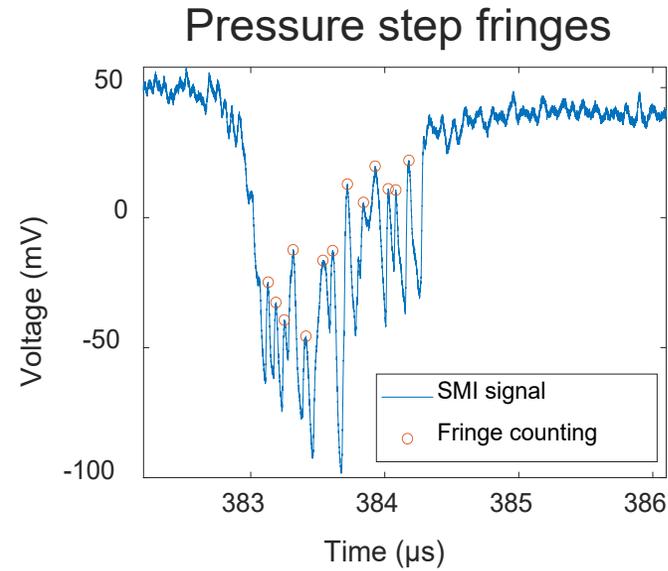
Shadowgraphy images at the exit of the open shock tube



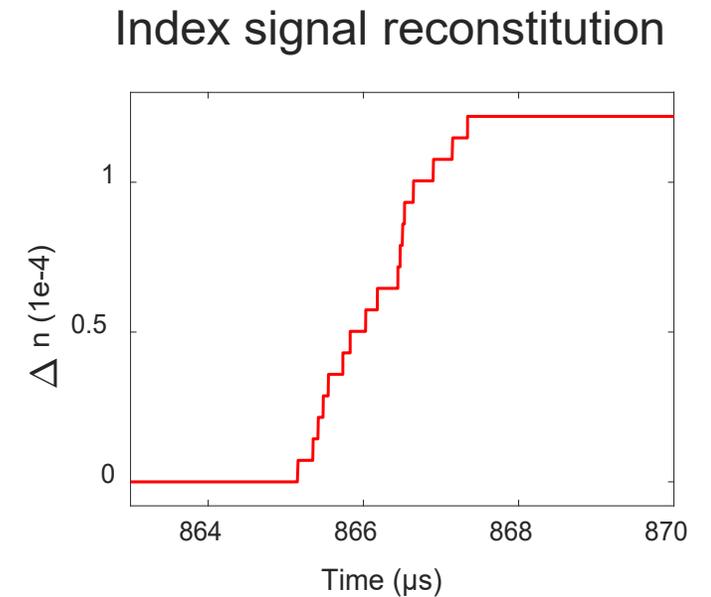
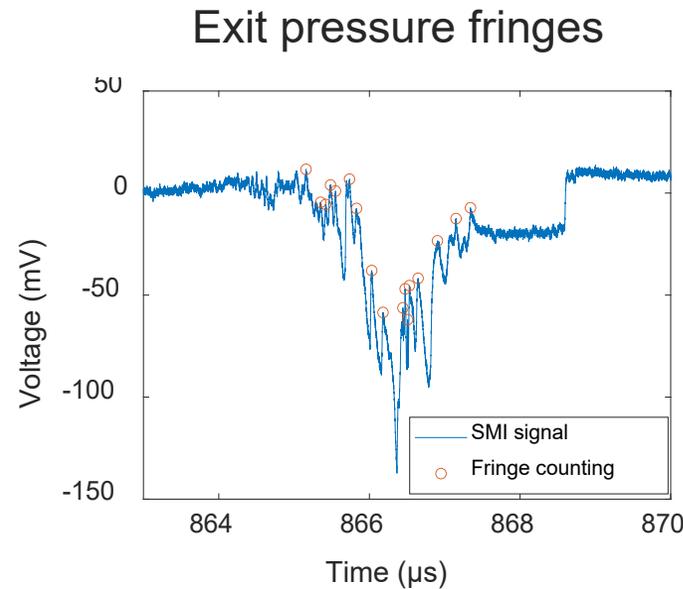
- Shock front sphericity and inhomogeneities influence the pressure measurement obtained by optical sensors
- The optical sensors measure the average pressure along the laser beam

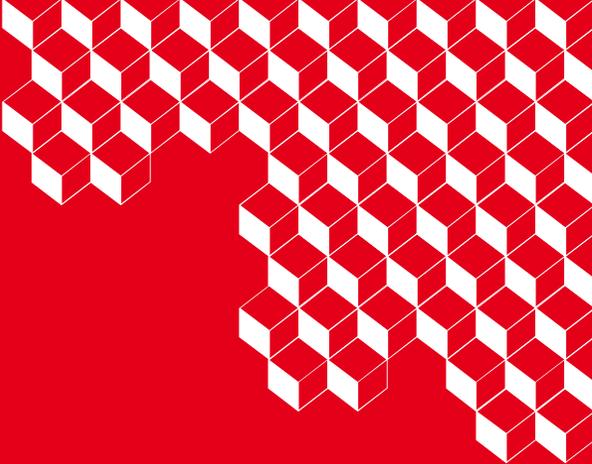
SMI sensor results

- **Incident pressure** measured fringes are nearly periodic with a rise time $\sim 1 \mu\text{s}$



- **Exit pressure:** fringes are aperiodic with a rise time $\sim 2 \mu\text{s}$, the spherical shock front creates inhomogeneities in the refractive index profile along the laser beam





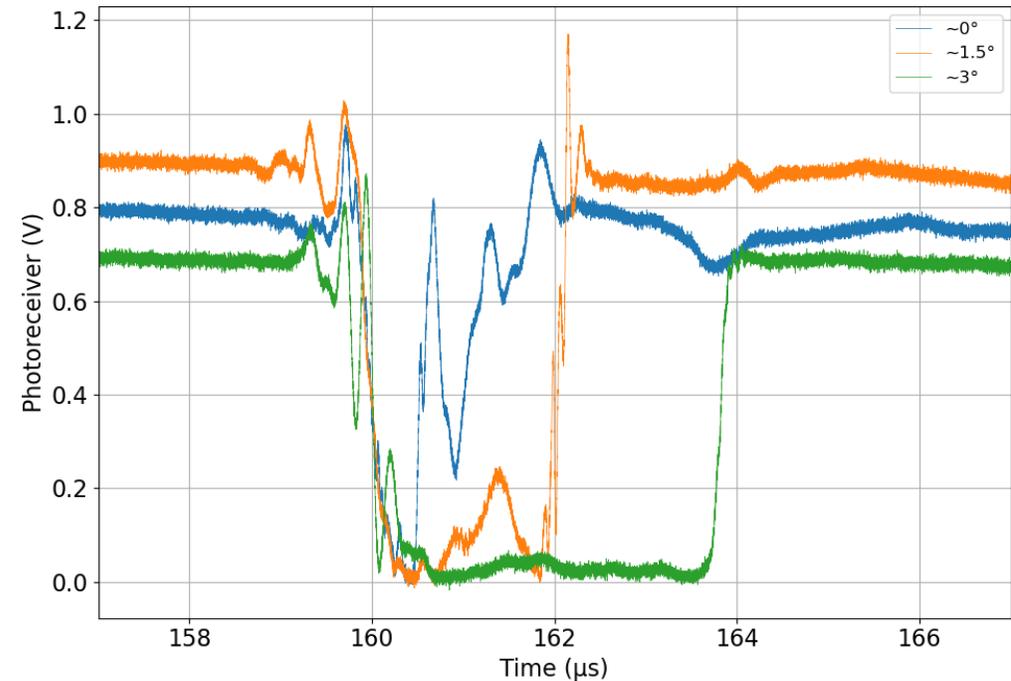
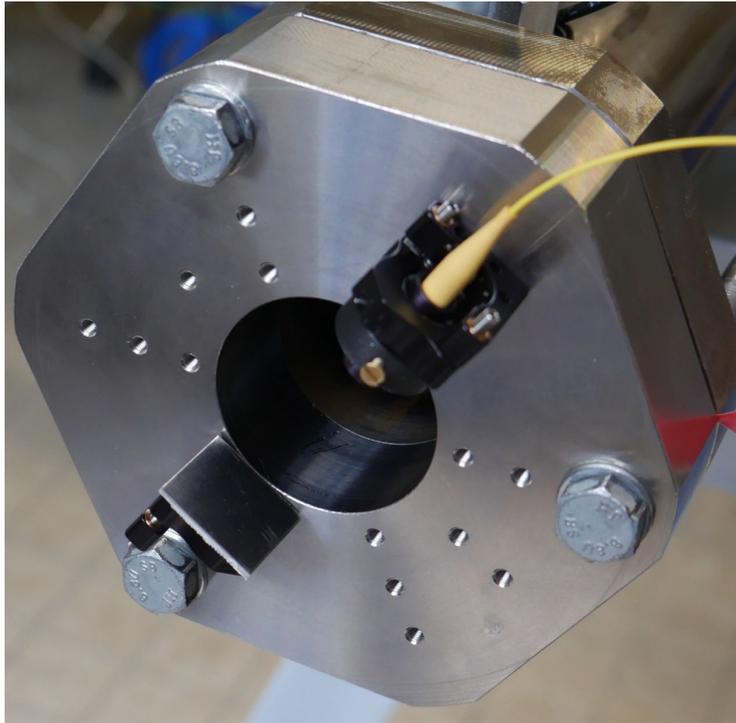
“ Can Triature PDV be used for overpressure measurements?

Objectives:

- Use of fiber probes
- Continuous measurement of the refractive index variation

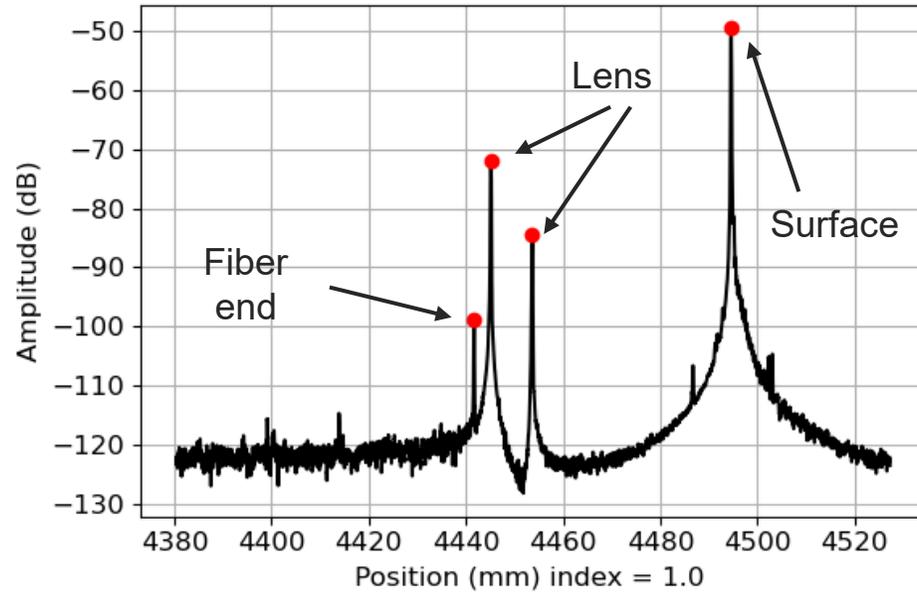
Transmission through a shock wave

- Compare to the SMI sensor, 1st PDV experiments were not very contrasted and reproducible
- Direct back and forward transmission tests through a shock wave with a collimator

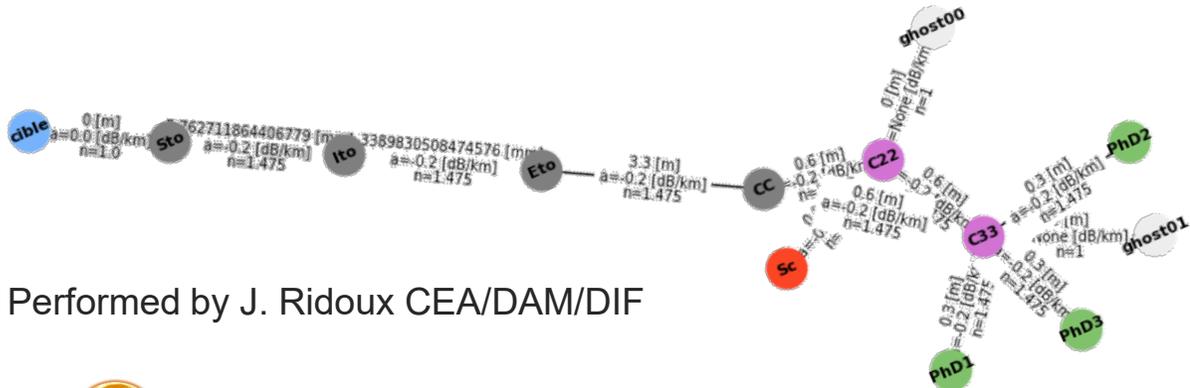


- Back coupling into a single mode fiber is not very tolerant
- The polarization does not seem to be an issue
- A focuser showed less attenuation

Is the lens coating sufficient ?

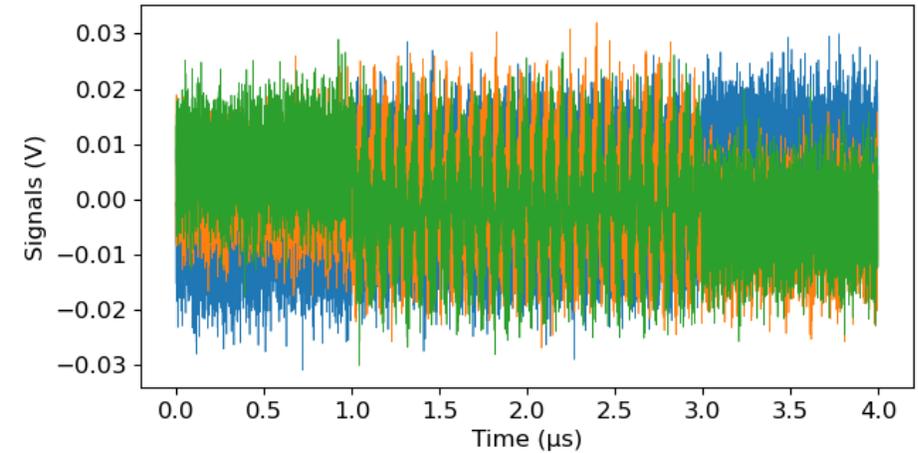


PDV simulation with all reflections

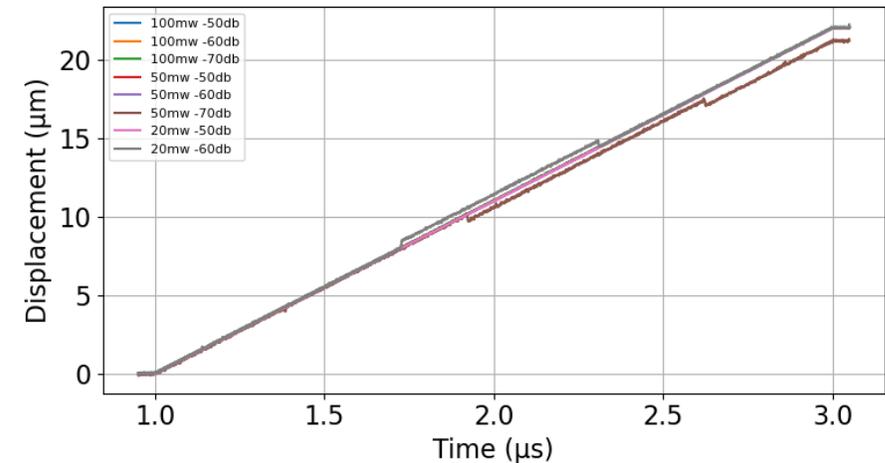


Performed by J. Ridoux CEA/DAM/DIF

Example of simulated signals with high noise and low target reflection



No significant issue after signal processing



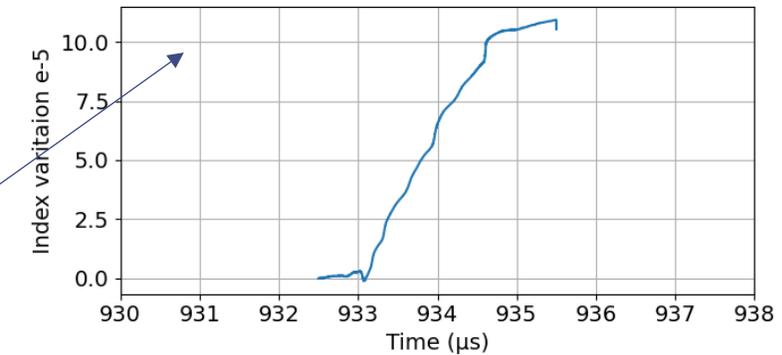
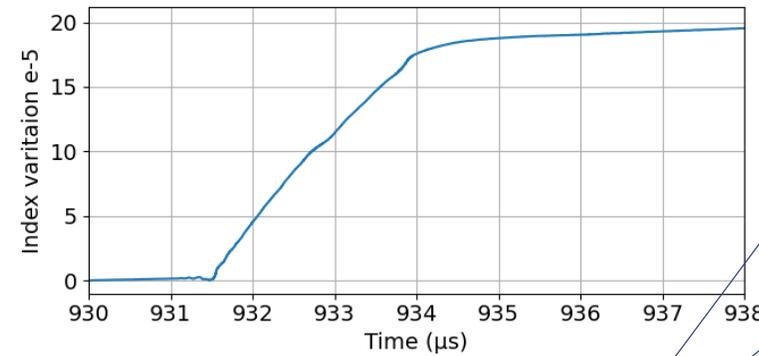
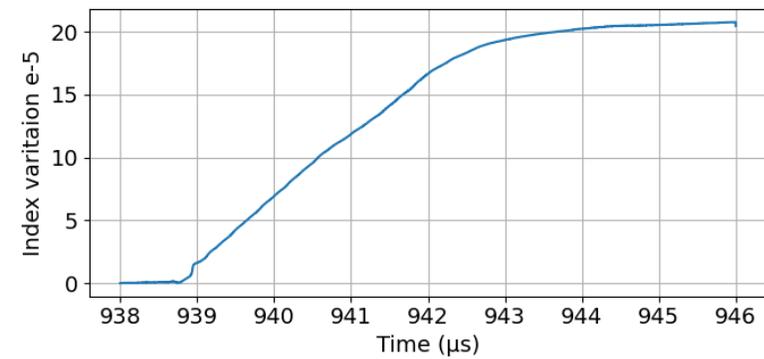
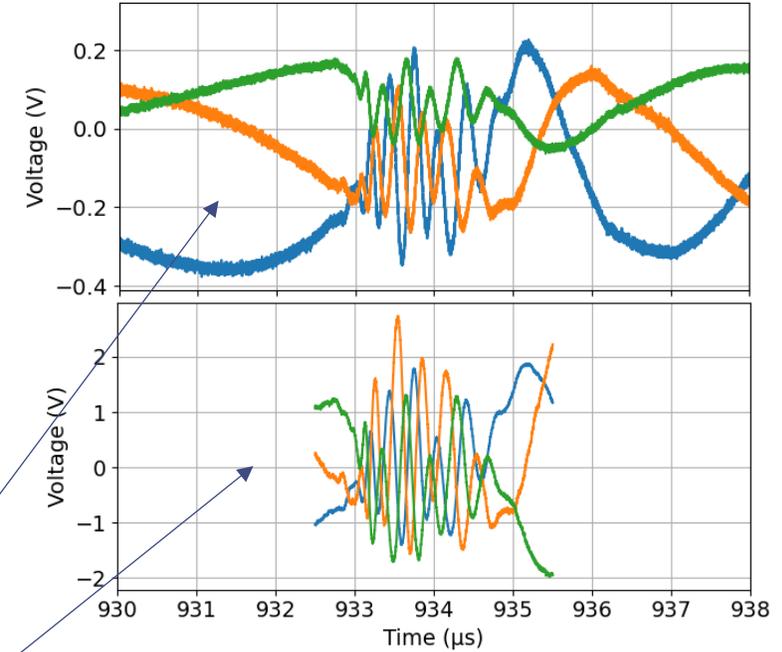
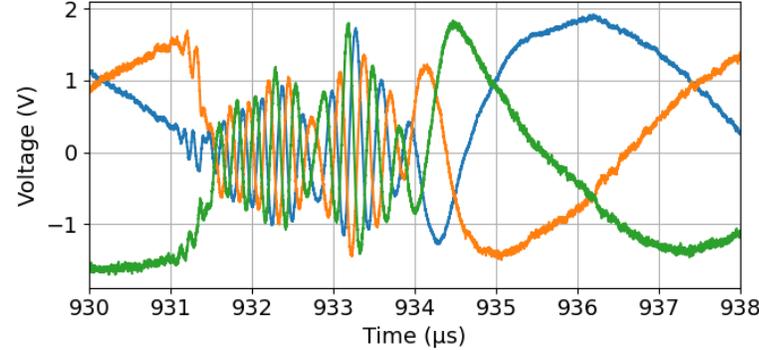
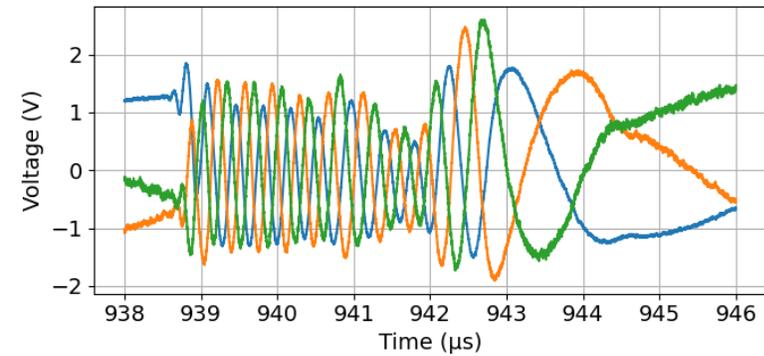
Triature PDV results at different angles



~4.2°

~3.8°

~1.4°



- Almost perfect signals
- Easy signal processing
- Correct refractive index value

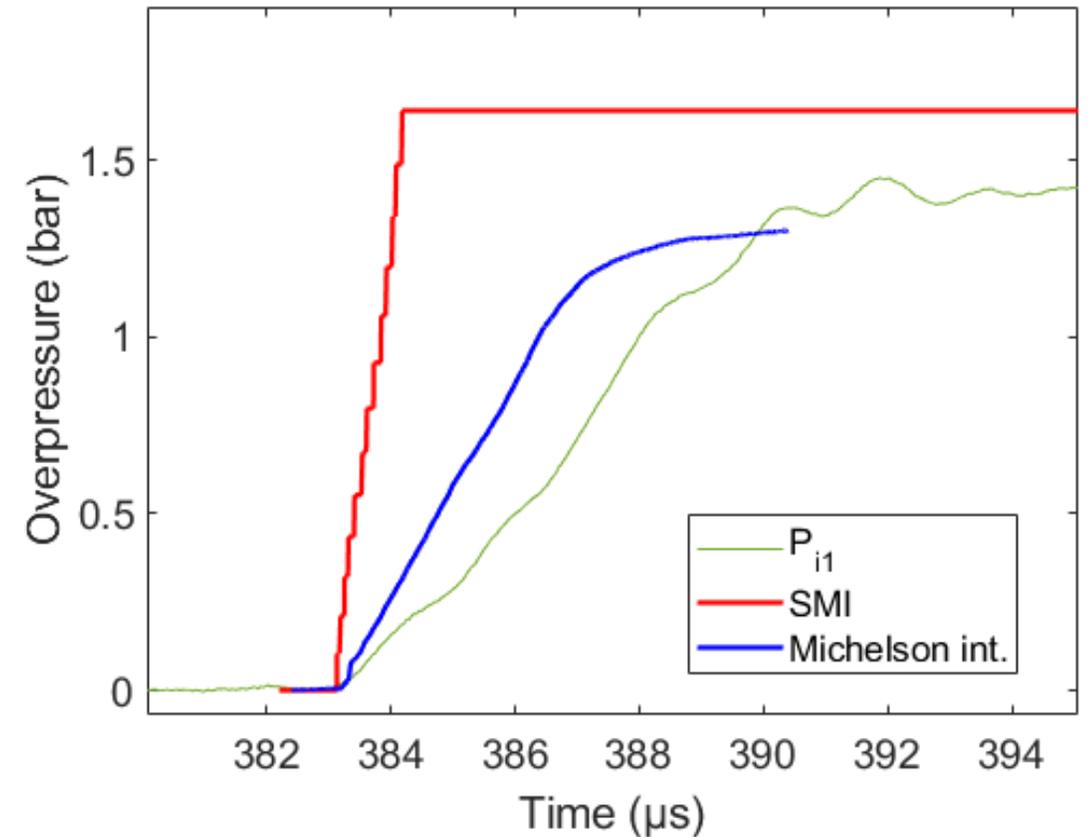
- Lower contrast
- Pretreatment needed
- Refractive index underestimated



Comparison with reference pressure sensors

- Different experiments (not exactly the same pressure levels)
- The model from slide 5 was used to get the overpressure
- The SMI sensor has the fastest response so far, it is less sensitive to index variation along the beam
- Triature PDV is limited by the back coupling of the signal but provides a continuous measurement

These remain primary results



Conclusion



- Optical measurements were made through planar and spherical shock waves using a metrological shock tube
- A comparison between SMI sensor and Triature PDV for refractive index measurement along a laser beam was made
- Good performance of the SMI sensor in accordance with reference sensors but the resolution is visible at low pressure levels
- Triature PDV suffers from single mode probes but seems not sensitive to polarization and interface reflectivities
- Triature PDV delivers a much better resolution

Perspectives

SMI

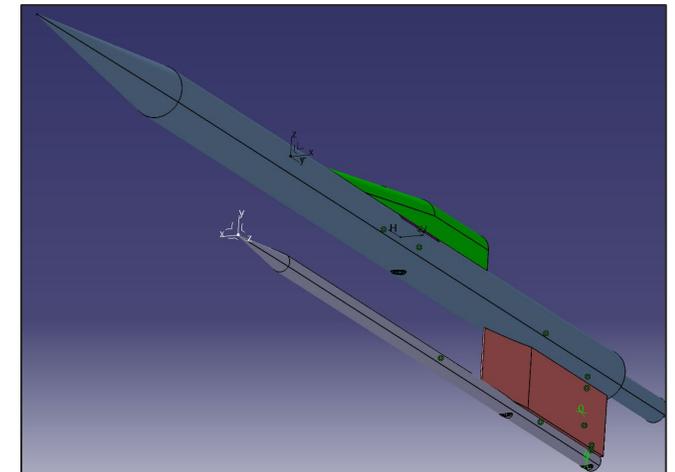
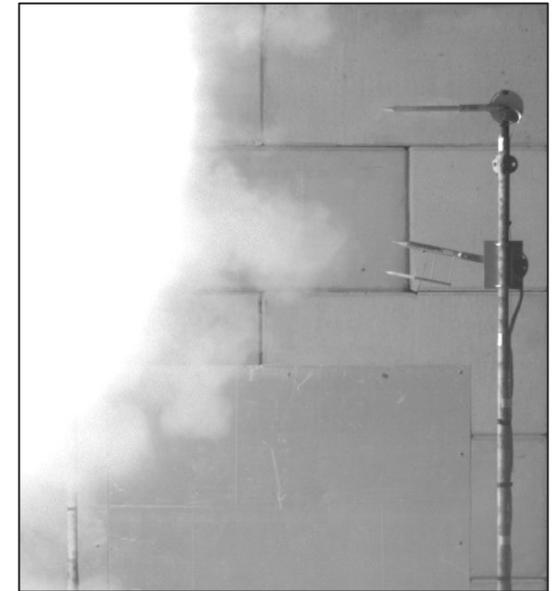
- Investigate more advanced signal processing techniques to improve resolution
- Electronics with higher bandwidth (>200 MHz)
- Possibly fiber probing
- Confirm initial results obtained in open field experiments (not shown here)

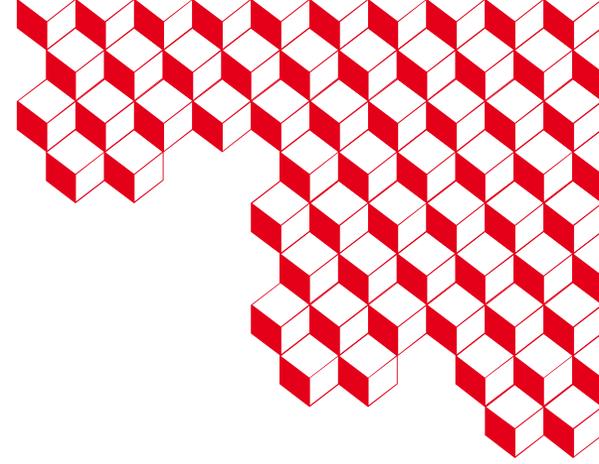
Triature PDV

- Optimization of the light coupling to ensure good interference fringes contrast
- Possibly get a Class 1 laser system
- Open field experiments with a “double pencil probe setup” already designed

Both for Triature PDV and SMI sensor

- Signal processing to deconvolute the wavefront curvature



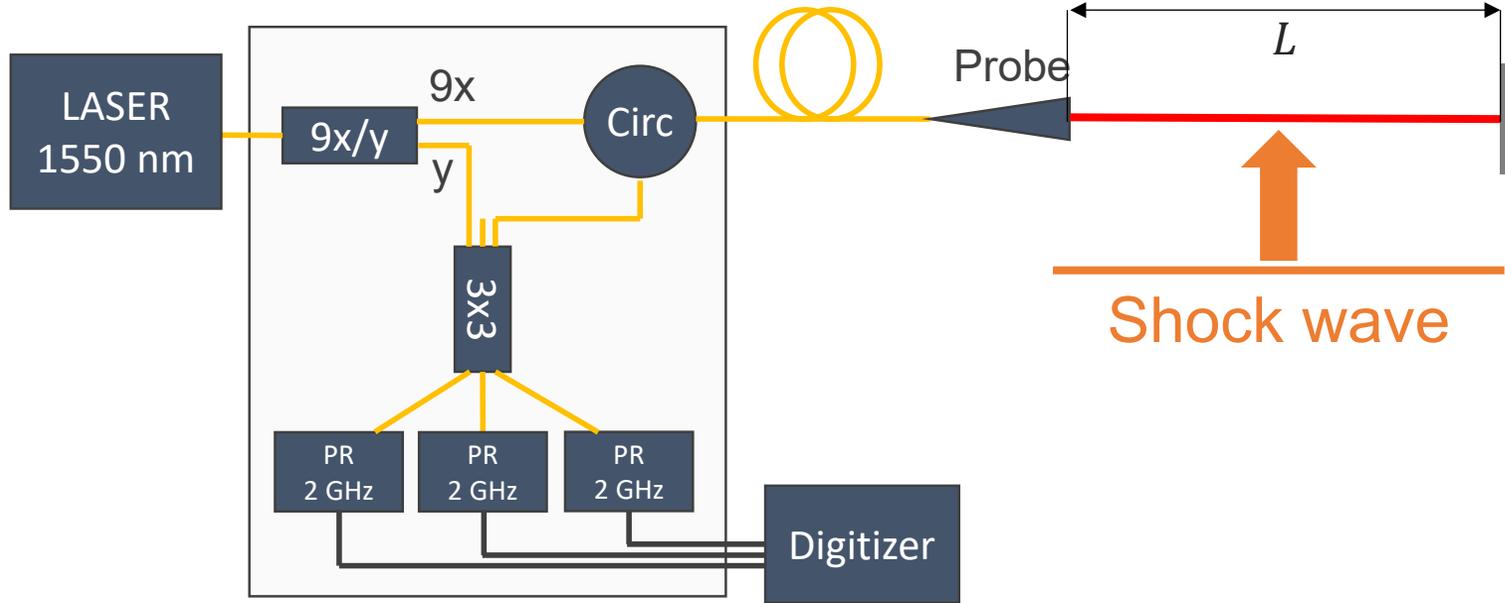


Thank you for your attention

7/24/2025



Triature Equations



$$\begin{cases} I_1(t) = I_0(t) \cos \left[4\pi \cdot \frac{\Delta n(t) \cdot L}{\lambda} + \Delta\varphi \right], \\ I_2(t) = I_0(t) \cos \left[4\pi \cdot \frac{\Delta n(t) \cdot L}{\lambda} + \Delta\varphi + \frac{2\pi}{3} \right], \\ I_3(t) = I_0(t) \cos \left[4\pi \cdot \frac{\Delta n(t) \cdot L}{\lambda} + \Delta\varphi - \frac{2\pi}{3} \right], \end{cases}$$

$$\begin{cases} S_1(t) = -3 \frac{I_2(t) + I_3(t)}{I_1(t) + I_2(t) + I_3(t)}, \\ S_2(t) = \sqrt{3} \frac{I_3(t) - I_2(t)}{I_1(t) + I_2(t) + I_3(t)}, \end{cases}$$

$$\Delta n(t) = \frac{\lambda}{2 \cdot L} \cdot \frac{1}{2\pi} \cdot \arctan \left(\frac{S_2(t)}{S_1(t) + 2} \right)$$