LWIR Photonic Doppler Velocimetry system for shock and detonation sensing

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Outline

Context and motivations

- Non intrusive diagnostics

- Characterization of new conventional explosive compounds

  - Pop-plot test

  - Gap test

  - …

- Measuring events in the material's core

  - Shock velocity
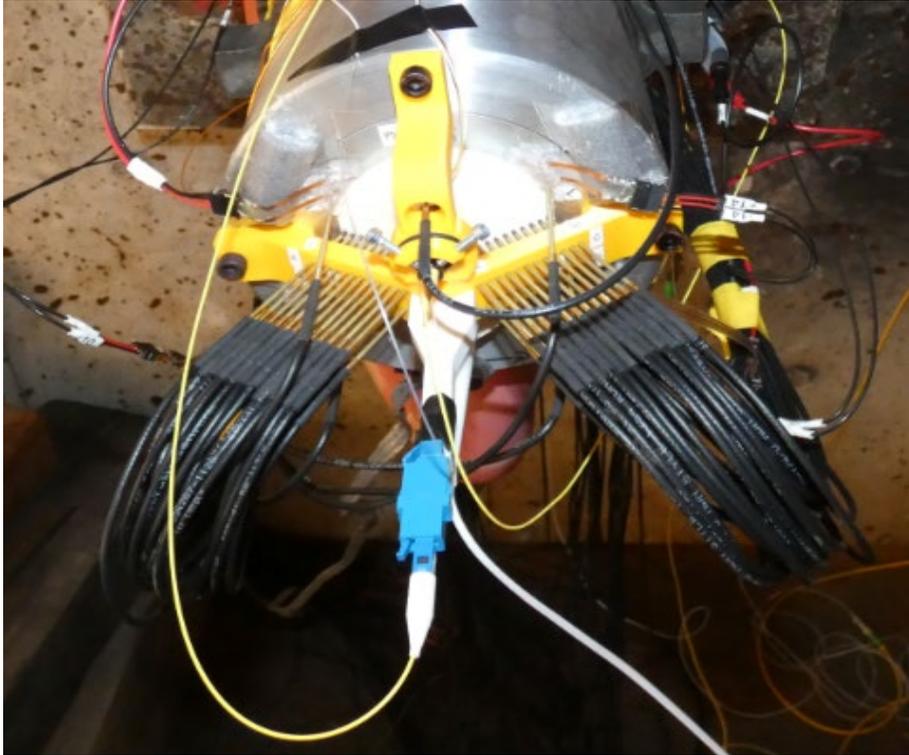
  - Detonation velocity

  - Initiation depth

  - …

Brian C. Glancy, Harold W. Sandusky, and Albert D. Krall "Microwave interferometry of shock waves. II. Reacting porous media" Journal of Applied Physics 74, 6328 (1993)
Bel'skii, V. M., Mikhailov, A. L., Rodionov, A. V. and Sedov, A. A. "Microwave Diagnostics of Shock-Wave and Detonation Processes" Combustion, Explosion and Shock Waves. 47, 639–650. (2011)
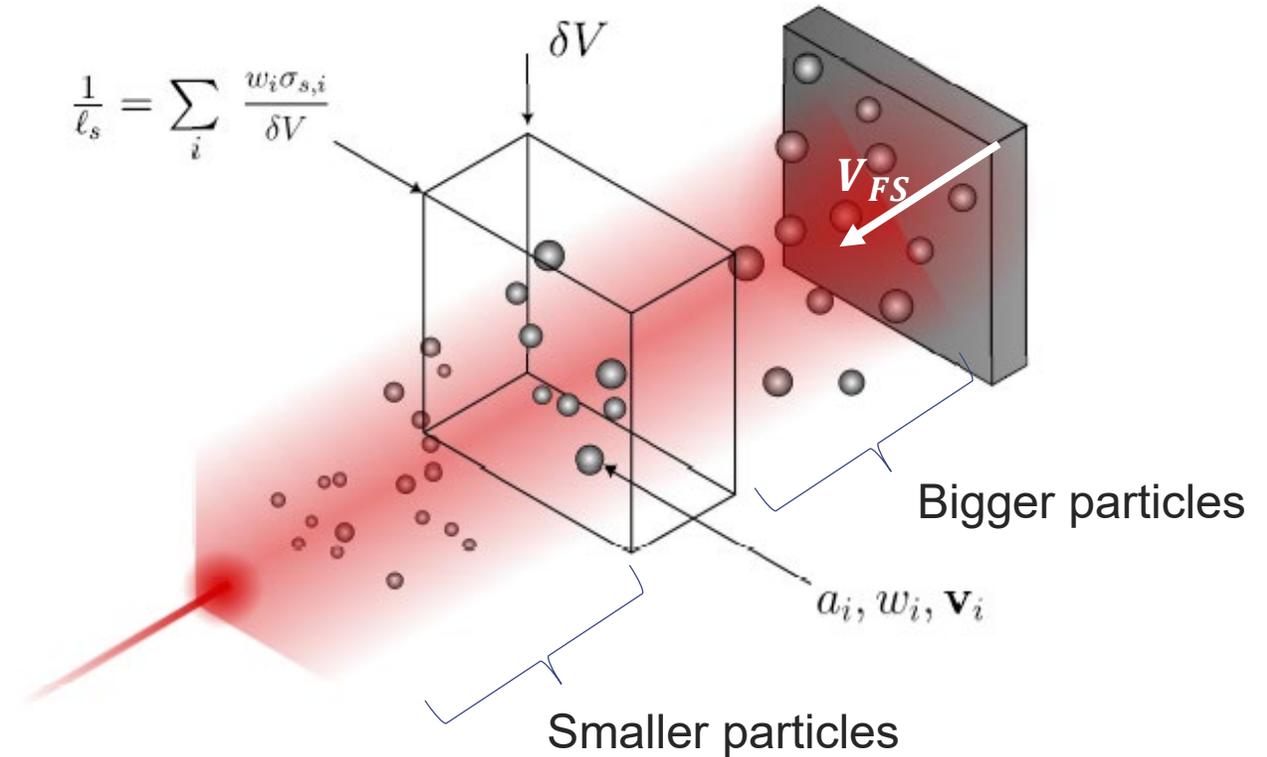

Impact on explosive compound

Context and motivations

Shock wave velocity and detonation
inside a material

Velocity tracking of bigger ejectas
and free surface velocity

$$\frac{1}{\ell_s} = \sum_i \frac{w_i \sigma_{s,i}}{\delta V}$$

δV

V_{FS}

Bigger particles

$a_i, w_i, \mathbf{v}_i$

Smaller particles

WO 2023/242498 A1 : Velocimeter in the mid-infrared range for measuring velocity

Millimeter-Wave interferometer

Target   Impactor

Probe

Millimeter-wave
interferometer

D
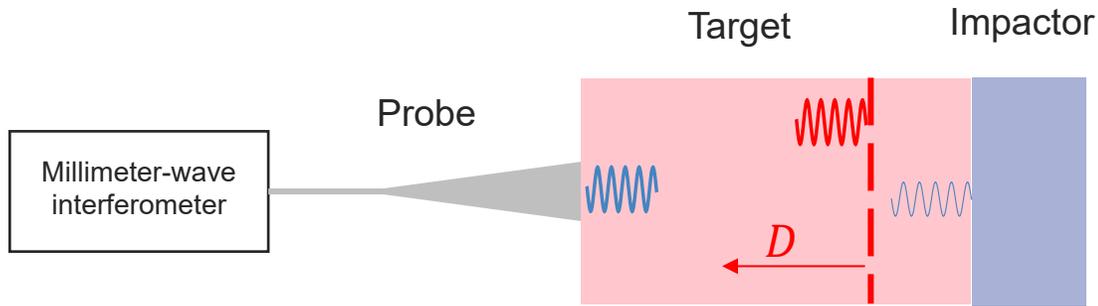
WWW Millimeter-Wave interferometer emission
frequency 94 GHz

WWW Doppler frequency of the impactor

WWW Doppler frequency of the shock wave

- *in situ* shock wave velocity measurement by Doppler effect
    - Most materials are transparent in the mm-wave region
    - Refractive index needed

- Few interference fringes (λ = 3.3 mm) → Limited time resolution

- Phase analysis by quadrature processing
    - Wave position
    - Velocity extraction after time derivative

- Beam diameter ~ 20 mm → Spatial resolution limit

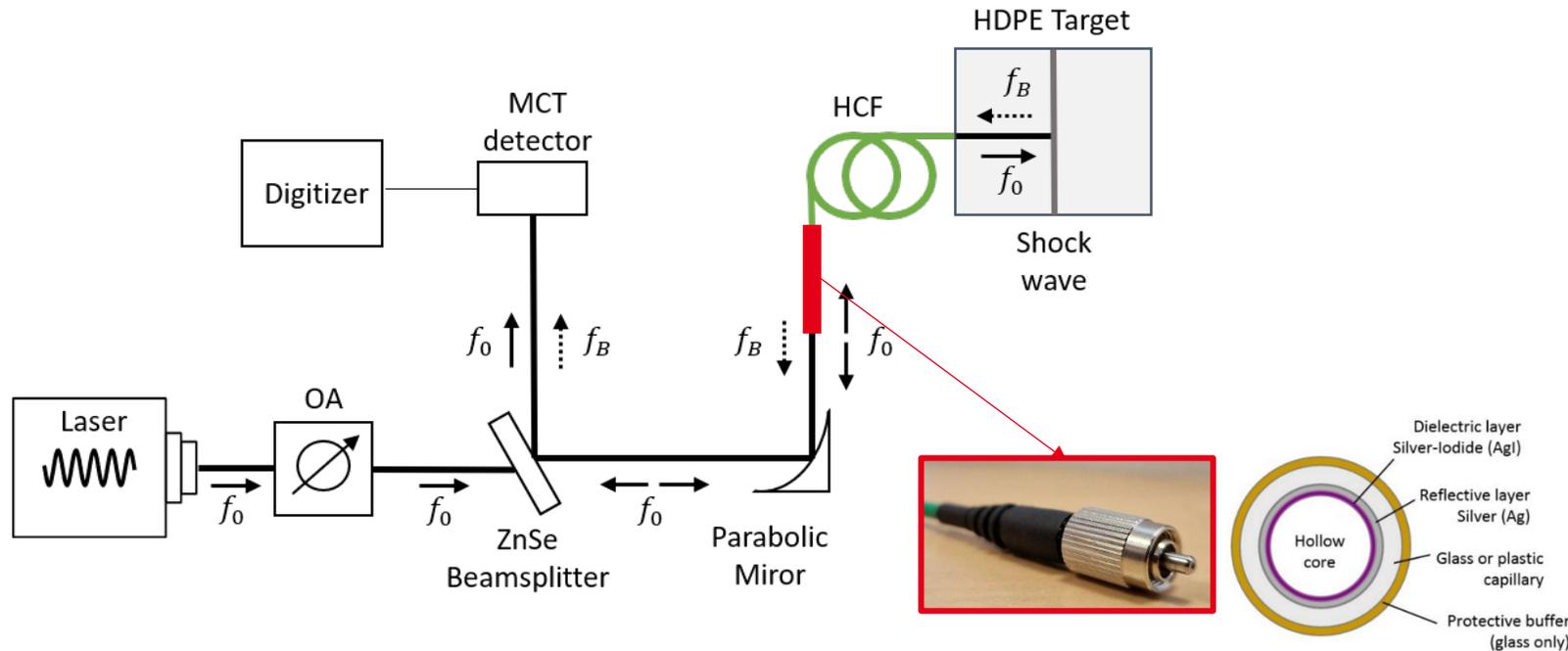➡ **How to improve the spatio-temporal resolution for shock velocity tracking ?**

Long Wave InfraRed wavelength (8-12 µm)

System	PDV	LWIR PDV	mm-wave Interferometer
Energetic Material transparency	No	Yes	Yes
Spatial resolution	0.1 mm	3 mm	20 mm
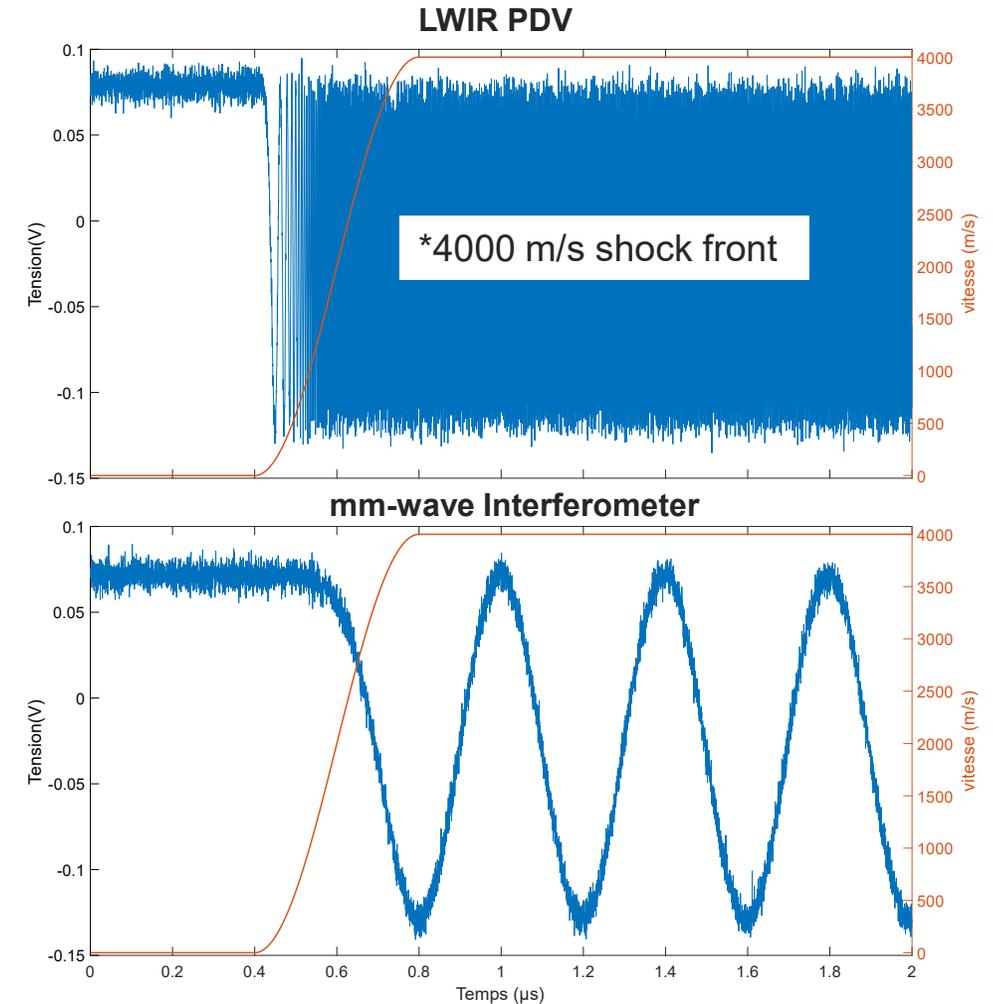
Towards a system measuring free surface, shock velocities and particles

LWIR PDV 1st design

Laser Source

- CO_2 Laser (Access Laser)
- 10.7 µm wavelength
- Optical power ~ 2W

Remote measurement

- Hollow core fiber (HCF) from Guiding Photonics
- 300 µm inner diameter
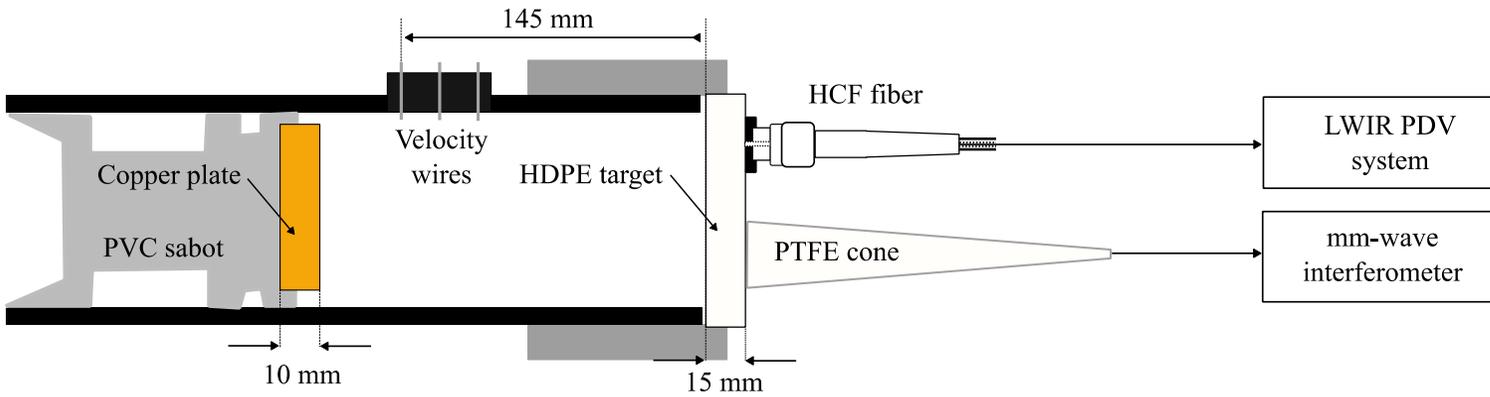- 1 dB/m losses
- Single mode fiber $\lambda > 8$ µm

Detection

- Amplified MCT sensor (Vigo Photonics)
  - Responsivity 700 V/W
  - BW [300Hz-750 MHz]

- Reference beam on the metallic connector

- System calibrated on refractive and diffuse materials ✔

- Free surface velocity measurement throughout partially transparent material such as High Density PolyEthylene (HDPE) ✔
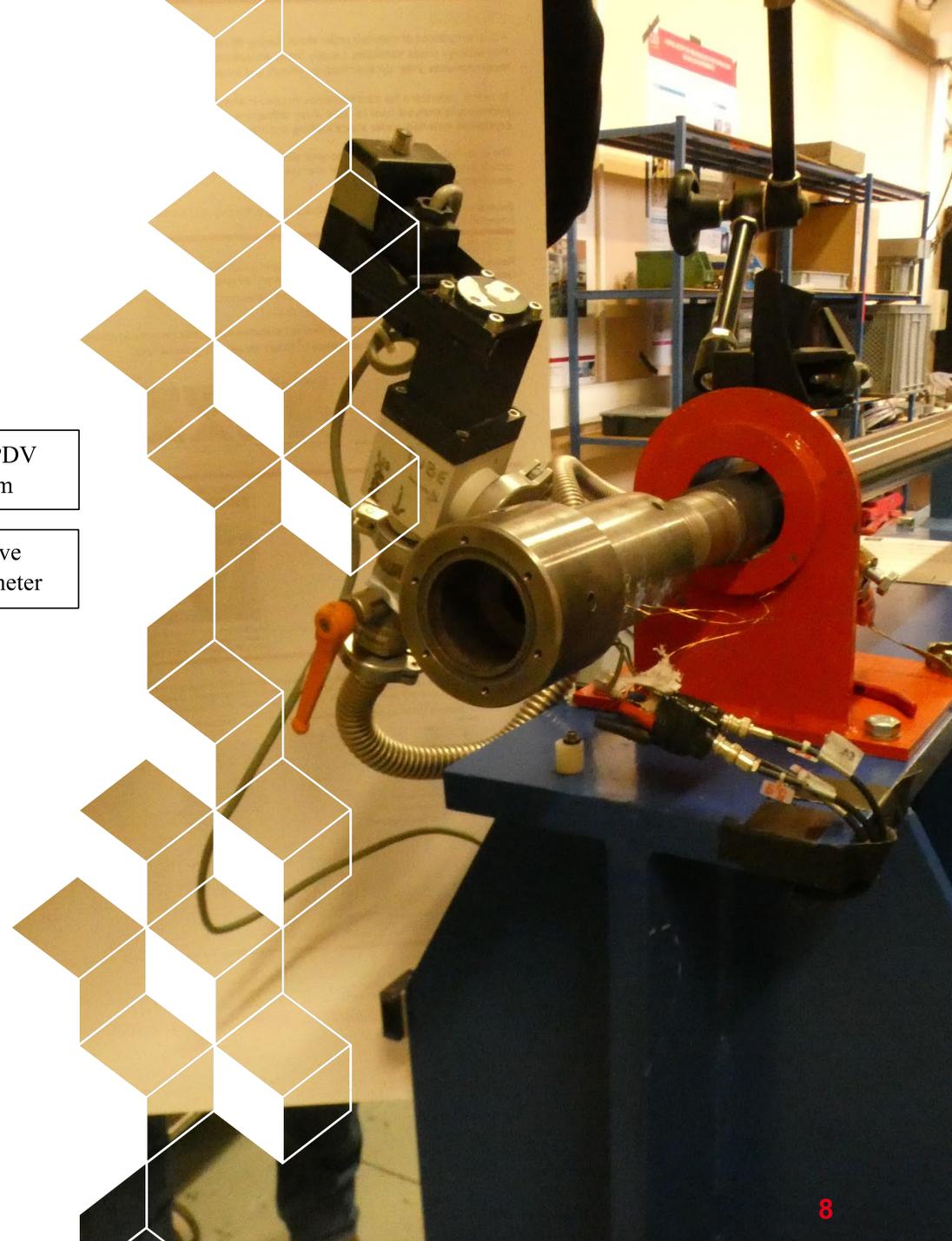
What about shock wave ?

Shock plate experiment

"Pyrene" Gas launcher:
- Max velocity: 750 m/s
- Tube diameter: 42 mm

145 mm

HCF fiber

Copper plate

PVC sabot

Velocity wires

HDPE target
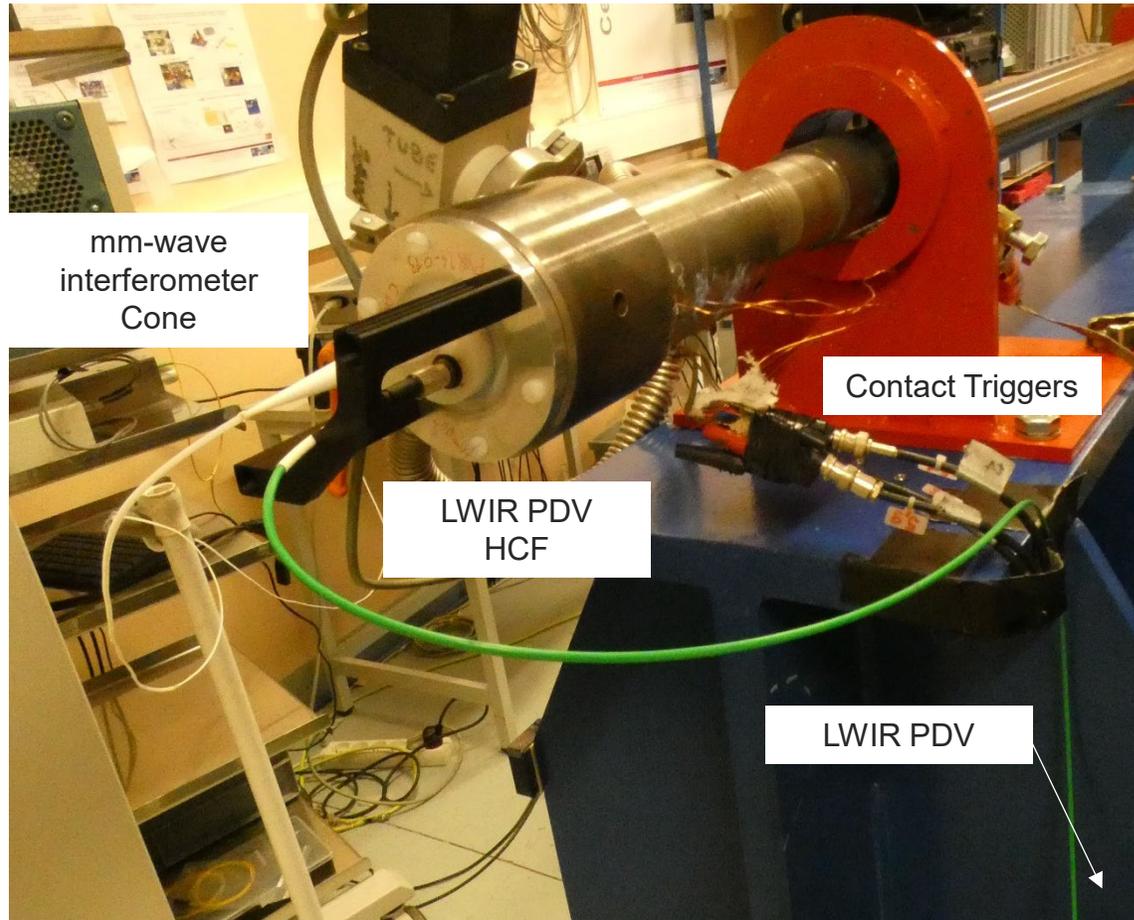
PTFE cone

LWIR PDV system

mm-wave interferometer

10 mm
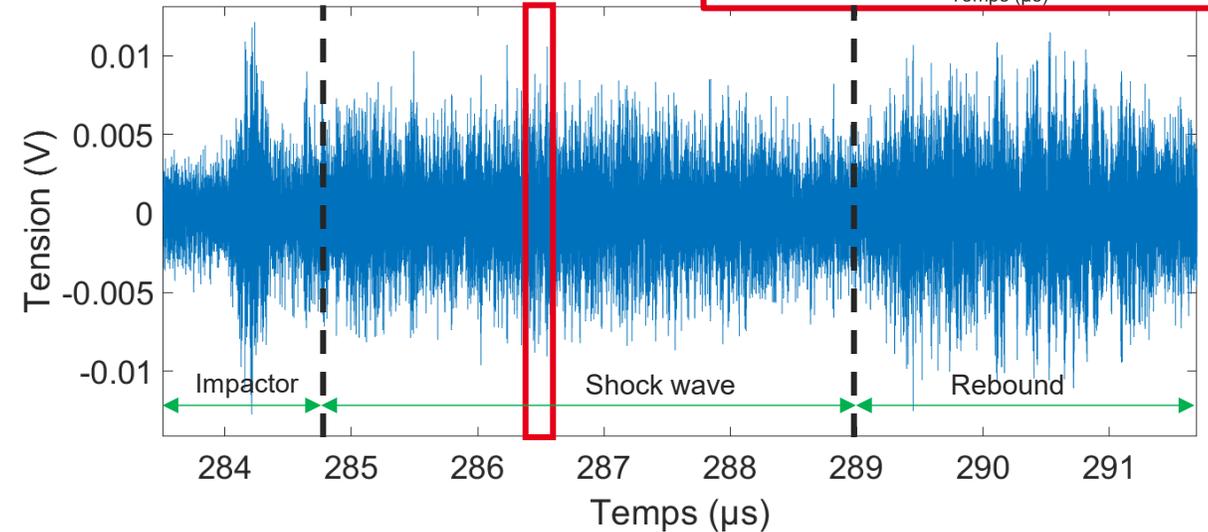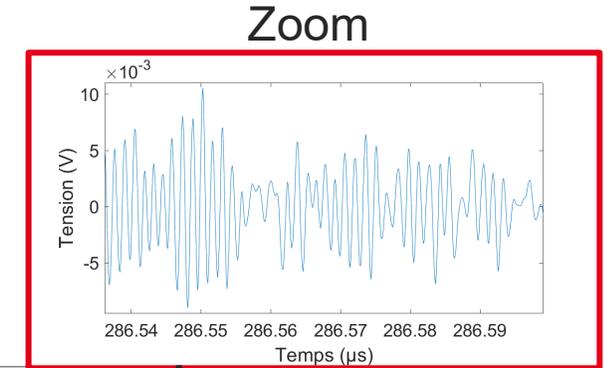
15 mm

Copper sabot

HDPE target

Impact at 500 m/s

Zoom

- Incident power on HDPE target 160 mW

- Propagation of the shock wave during 4.2 µs
- Return signal: ~100 nW
  - ↳ Max P2P amplitude: 26 mV
- Chronometry in agreement

Signal processing of the LWIR PDV experiment

- Band-pass filter: 80 MHz - 1 GHz

- STFT processing
  - Window type: Blackmann-Harris
  - FWHM: 50 ns
  - Window shift: 5 ns
  - Optical index: 1.52

- 2 velocity traces on the spectrogram
  - ~ 1000 m/s, impact velocity throughout the HDPE target (x2 second order reflection)
  - ~ 3000 m/s, shock wave velocity inside the HDPE target
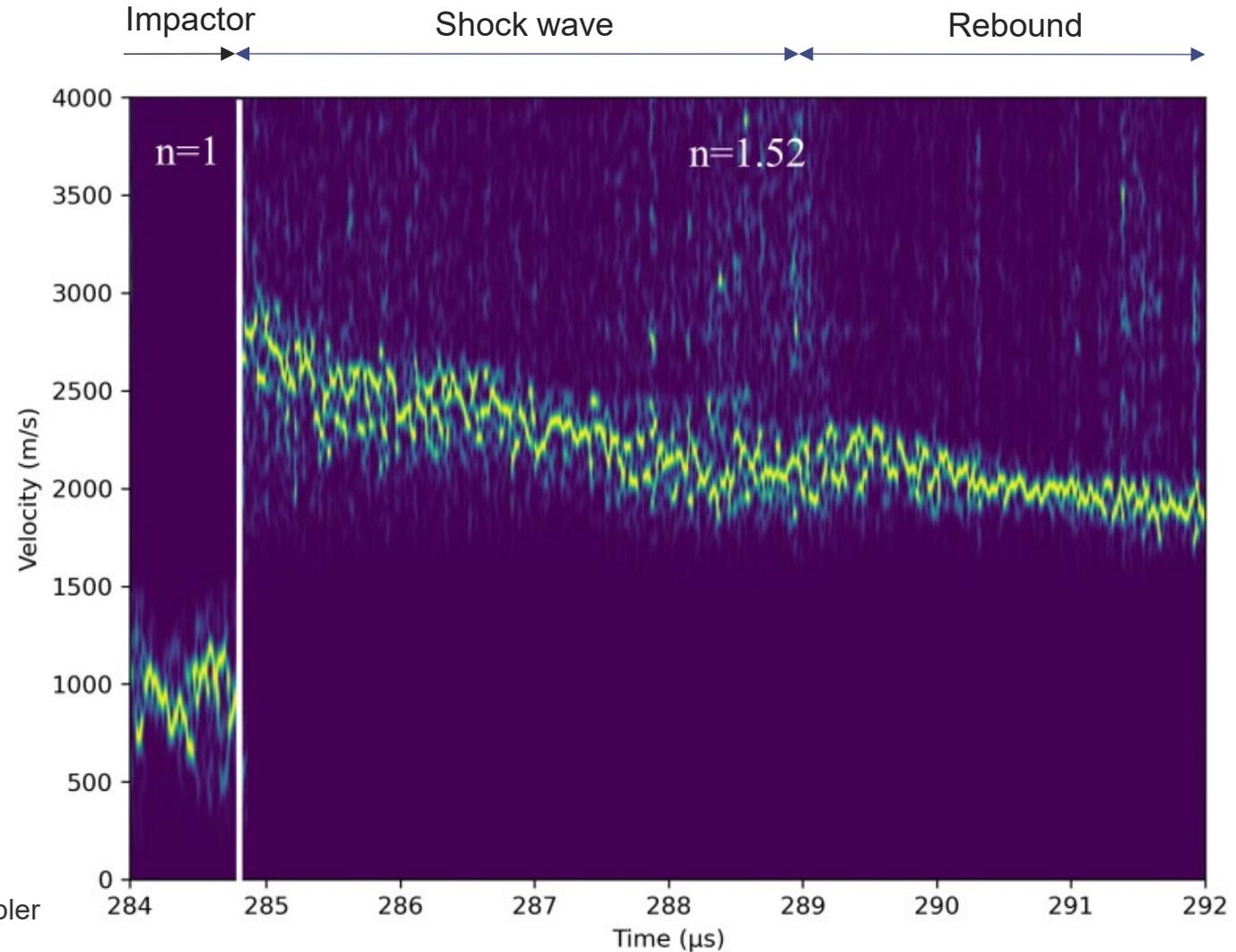
G. Lefrère, *et al*. « Shockwave measurement inside HDPE by photonic Doppler Velocimeter ," Rev.Sci.Instru. 2024 (submitted)
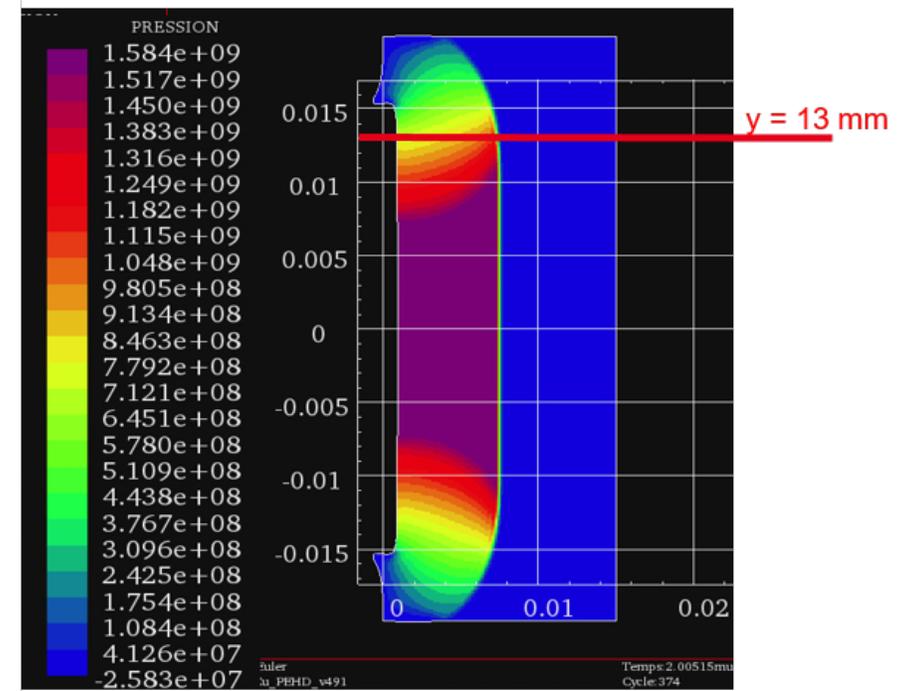
2D-Hydrodynamic simulation

2D Pressure evolution simulation

y = 13 mm
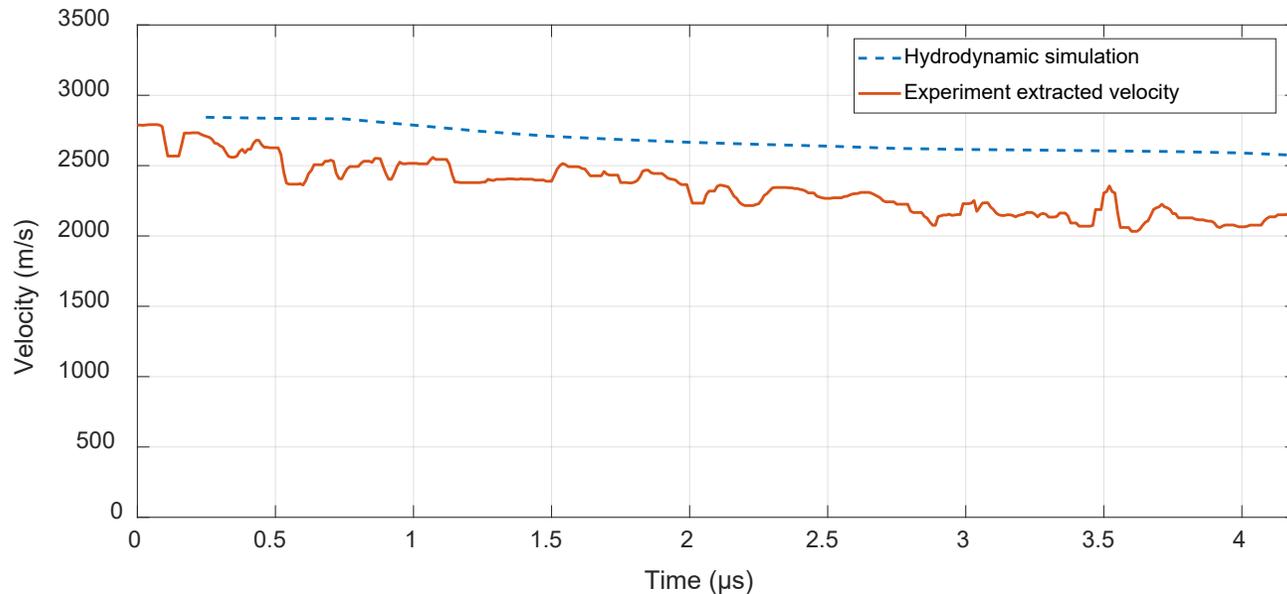
Equations of state (EOS) used:

Materials	ρ_0 (kg/m^3)	c_0 (m/s)	s
Copper	8897	3933	1.53
HDPE	952	2170	1.49

- 4.2 μs duration as expected
- Decreasing shock velocity with 8 to 20 % errors (certainly coming from the HDPE EOS)
- Decreasing pressure
- Curvature on the shock wave

➡ **The phenomenology between the simulation and the experiment is correct**

Conclusion

- Presentation of new PDV system working in the LWIR region

- Successful implementation on a gas launcher for conducting shock plate experiment
  - Measurement of shock wave velocity inside opaque material to standard PDV
  - Measurement of the flyer velocity throughout the target

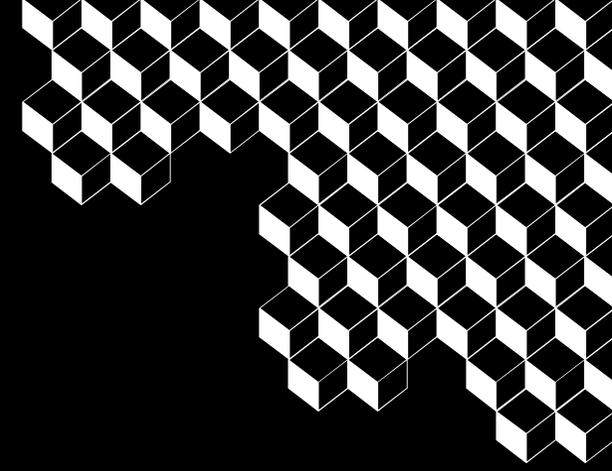- The 2D-simulation are close to the experiments

Perspectives

- Optimization of the coupling efficiency into the target

- Architecture upgrade
  - More compact
  - Addition of an acousto-optic modulator (AOM) for frequency shifting

- Experiments for shock wave and detonation sensing inside an energetic material

New architecture
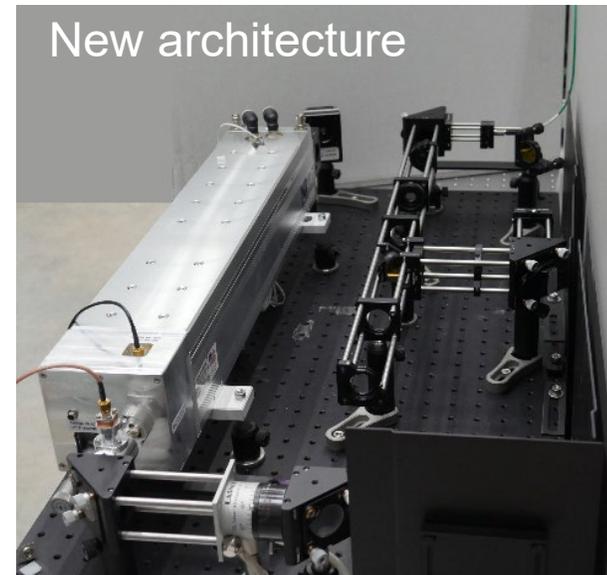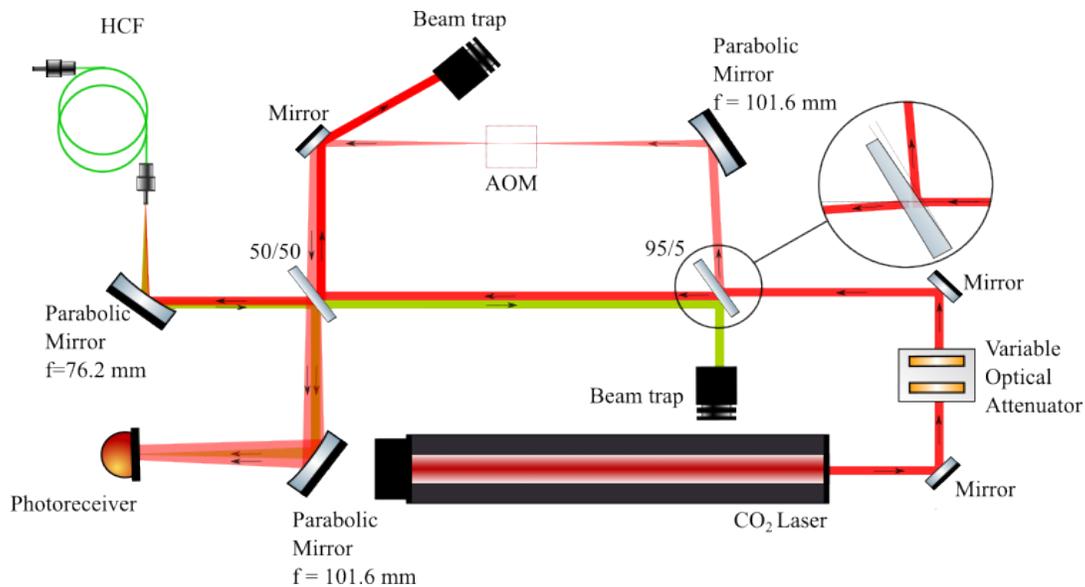
Implementation with explosive
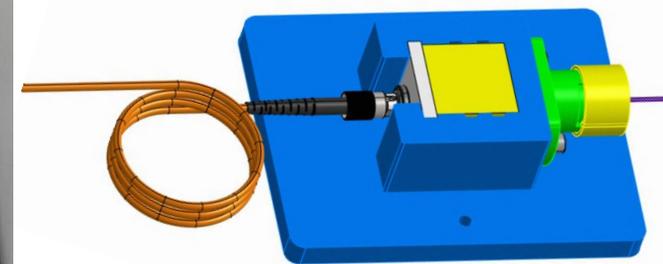
Thank you all

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