PDV characterization of the expanding detonation products of a TATB based high explosive

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6th Annual PDV Workshop, Livermore,
November 3-4, 2011

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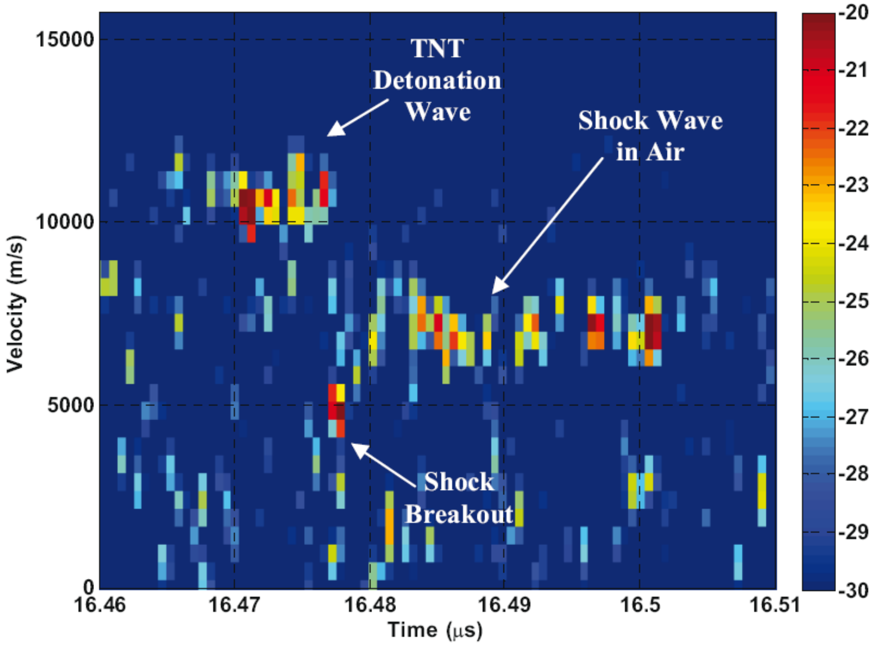
Background / Motivations

- PDV is now considered as a common diagnostic for shock physics and detonics experiments performed at CEA
- It has been used in many different kind of experiments:
  - > Nitromethane ignition and SDT observed with embedded PDV optical fibers
    - P. Mercier *et al.*, EPJ Web of Conference **10**, 00016 (2010)
    - P. Mercier *et al.*, Proc. SPIE **7429**, 742913 (2009)
  - > Measurement of the chemical reaction zone of detonating liquid explosives
    - V. Bouyer *et al.*, Shock Compression of Condensed Matter, CP1195, pp. 177-180 (2009)
  - > Measurement of the chemical reaction zone of solid explosives
    - V. Bouyer *et al.*, Shock Compression of Condensed Matter-2011
    - V. Bouyer *et al.*, EPJ Web of Conference **10**, 00030 (2010)
  - > Particle ejection resulting from high-explosive driven shock waves
    - J. Bénier *et al.*, DYMAT 2009, pp.289-294 (2009)
  - > Ns and fs laser induced spallation and fragmentation of solid targets
    - P. Mercier *et al.*, Shock Compression of Condensed Matter, CP1195, pp. 581-584 (2009)
    - P. Mercier *et al.*, Proc. SPIE **7429**, 742913 (2009)
- Recently, we started to apply it to the characterization of the expansion of detonation products from solid high explosives:
  - > First experiments on TATB
    - A. Sollier *et al.*, Shock Compression of Condensed Matter-2011
    - A. Sollier *et al.*, Proc. 28th Int. Symposium on Shock Waves (2011)

Background / Motivations

D. Holtkamp (LANL) demonstrated the ability of PDV system to measure the free surface velocity of expanding TNT detonation products, and also the detonation velocity inside the explosive during the last ns before breakout.



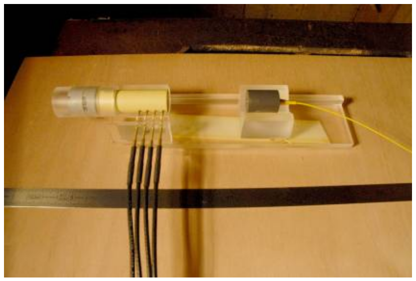
D.B. Holtkamp, 2006 *IEEE International Conference on Megagauss Magnetic Field Generation and Related Topics*, pp. 119-128 (2006).

Our objective:

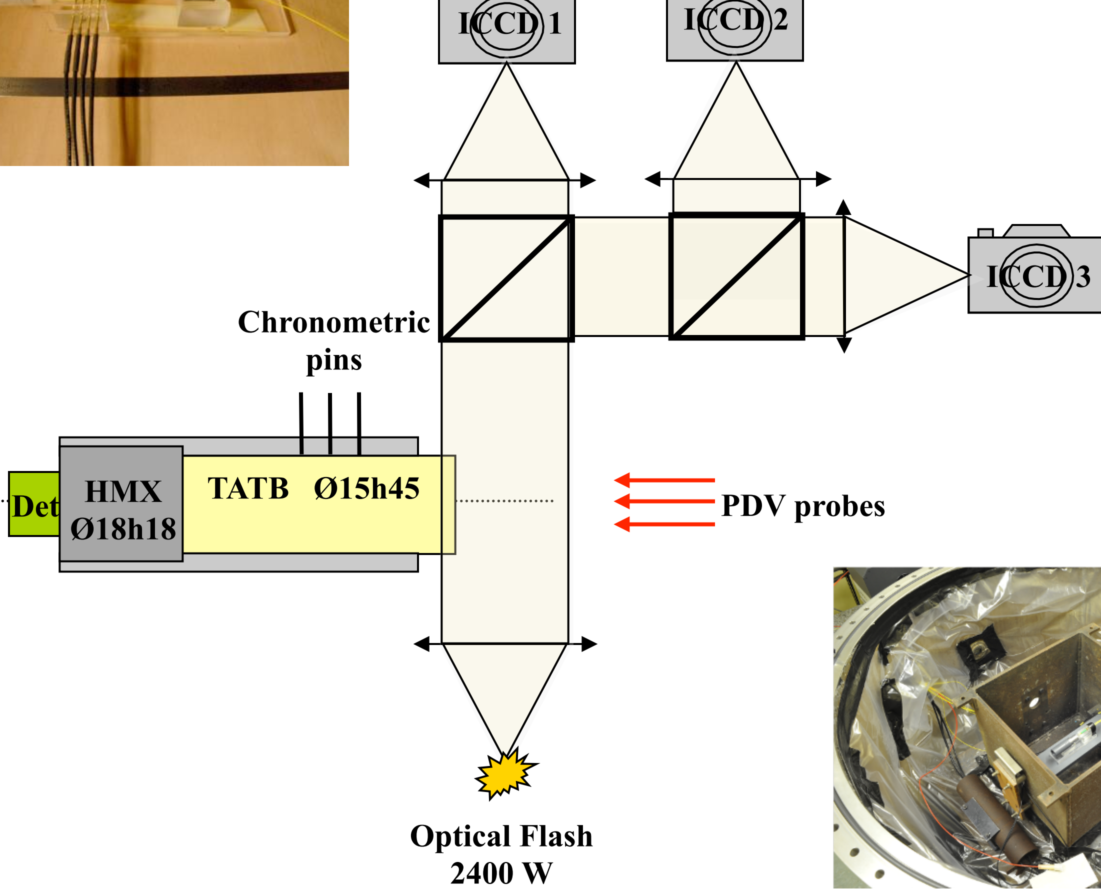
- Perform similar experiments on other high explosives using the 2 lasers PDV system developed at CEA.
- First experiments on a TATB composition:
  - Like TNT, TATB is under oxidized and produces a lot of solid carbon → facilitates PDV measurements ?
- Can we extract useful information about the reaction zone of the explosive from the PDV waveforms ?
  - New way for characterizing the chemical reaction zone without inducing any perturbation in the flow.

Experimental setup

- **Experiments performed under a ligth vacuum (20 mbar) or in air at atmospheric pressure**

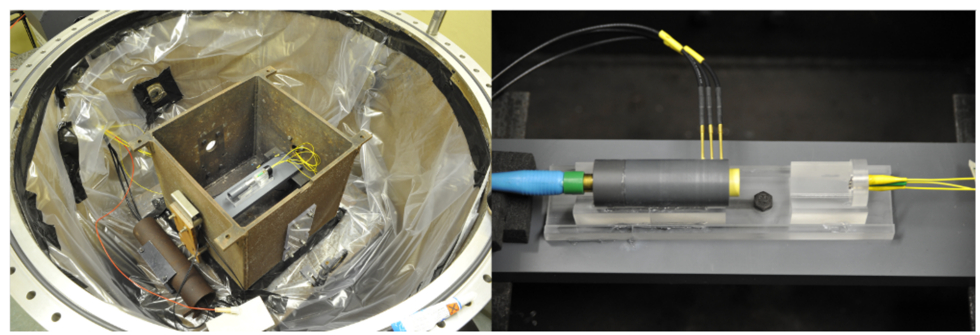


2 Dicam Pro and 1 Dicam HSFC cameras

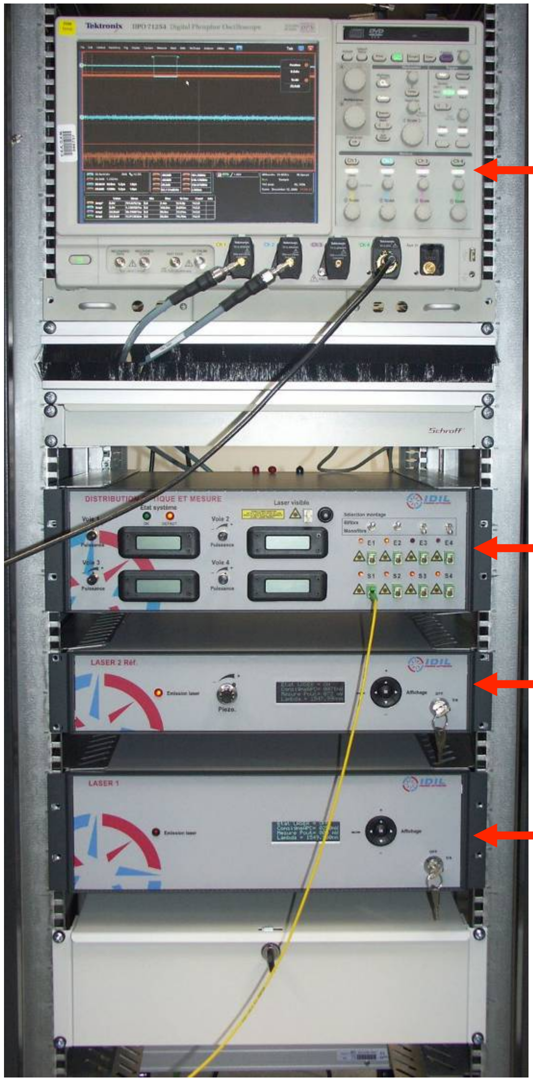


Diagnostics

- Chronometric pins
  - > detonation velocity,
- 4 channels PDV system
  - > time evolution of the free surface velocity,
- Digital high speed shadowgraphy
  - > mean free surface velocity and shape of the cloud of detonation products.



Photon Doppler Velocimetry setup (1/2)



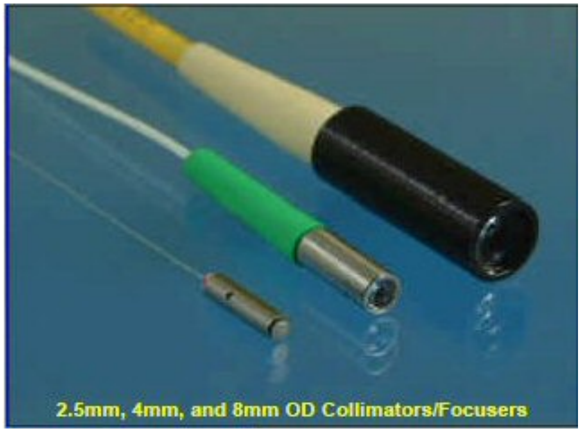
Tektronix DPO71254
4 channels digitizer
12.5 GHz, 50 GS/s

Detectors,
circulators, couplers

Frequency shifted
reference laser :
50 mW

Main laser
2 W, 4 channels

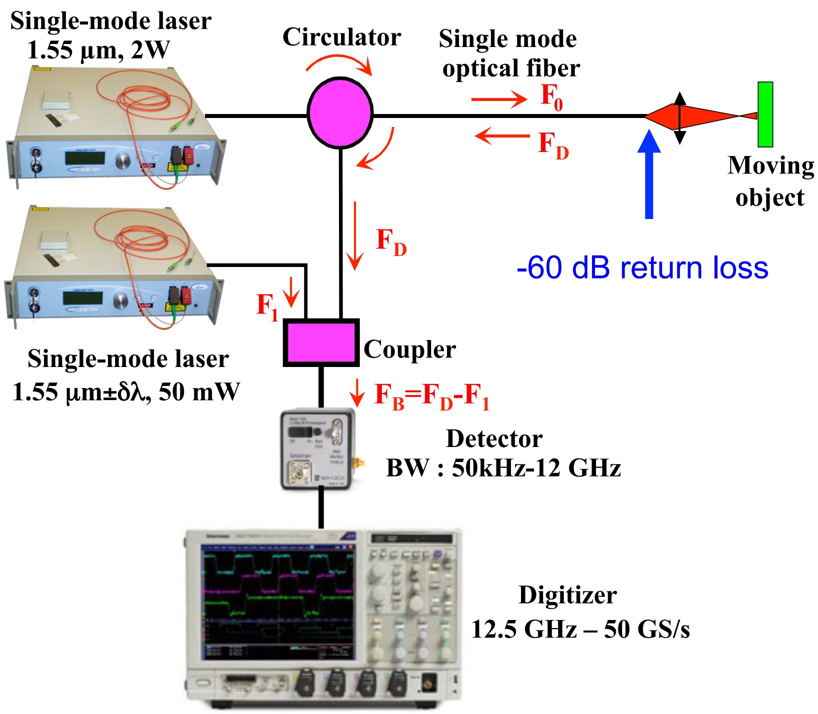
- CEA 2-lasers system developed in collaboration with IDIL.
- Cost ~160 k€ for 4 channels.
- About 15 units in operation at CEA.

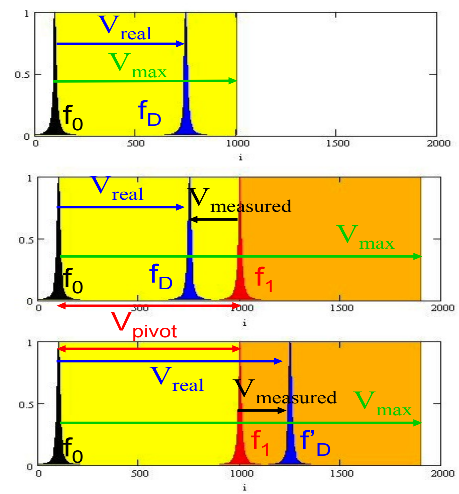


OZ Optics probes

Photon Doppler Velocimetry setup (2/2)

2 lasers, 1 single optical fiber setup





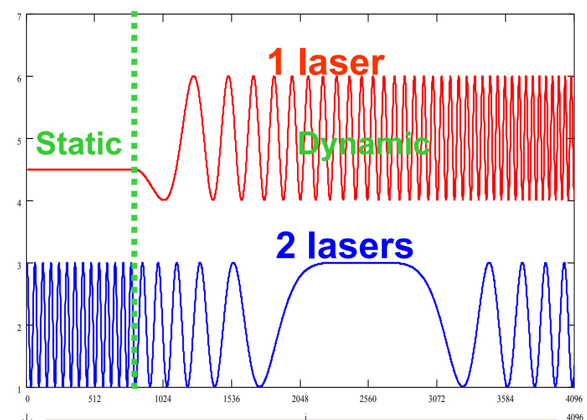
$$V = \frac{\lambda_0}{2}\Delta f$$

$$V_1 = \frac{\lambda_0}{2}\left(\Delta f_{max} - \Delta f\right)$$

$$V_2 = \frac{\lambda_0}{2}\left(\Delta f_{max} + \Delta f\right)$$

Doubled bandwidth: V_{max}~20 km/s but 2 solutions

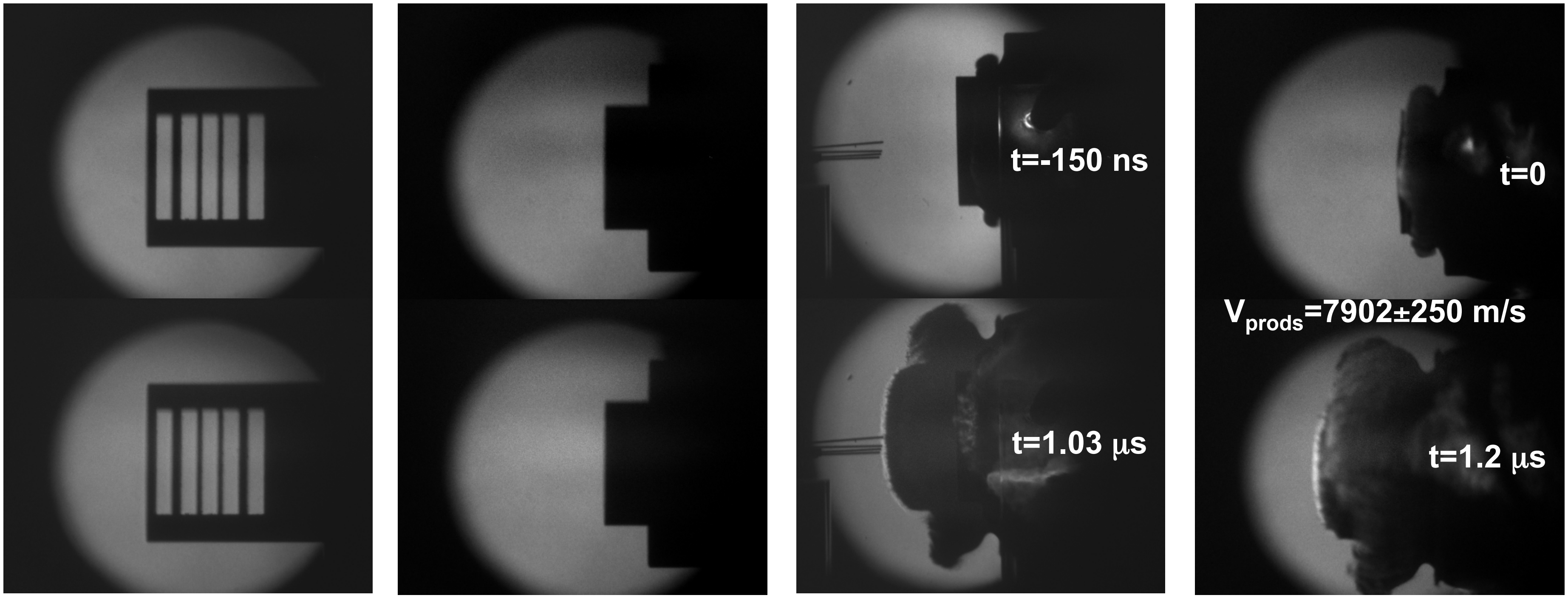
- 2nd laser used to provide reference ligth and to induce frequency offset
  - > Allow to double the bandwidth of the system
  - > Avoids low frequency noise
  - > Aids alignment



Static beats for adjustments

Digital high speed Shadowgraphy results

Reference | Static | Shot n°1 D=7545±173 m/s | Shot n°3 D=7532±172 m/s



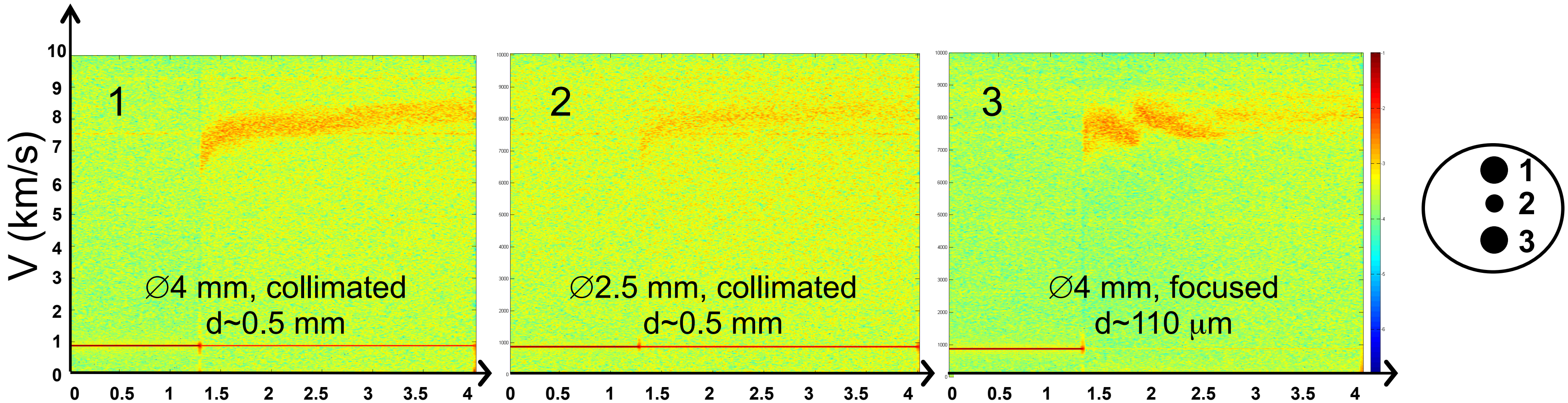
- Good overall reproducibility from shot to shot
  - > The cloud of detonation products stays opaque all along the expansion process
    - Lots of soots in the products like for TNT
  - > The leading edge of the cloud is almost plane for about 1 μs along the centerline
  - > Its mean expansion velocity is about 8 km/s
    - Good agreement with earlier studies

T.J. Ahrens *et al.*, JAP 42(2) 815 (1971)
A.I. Lyamkin and S.T. Popov, Comb. Expl. Shock Waves 27(5), 620 (1992)

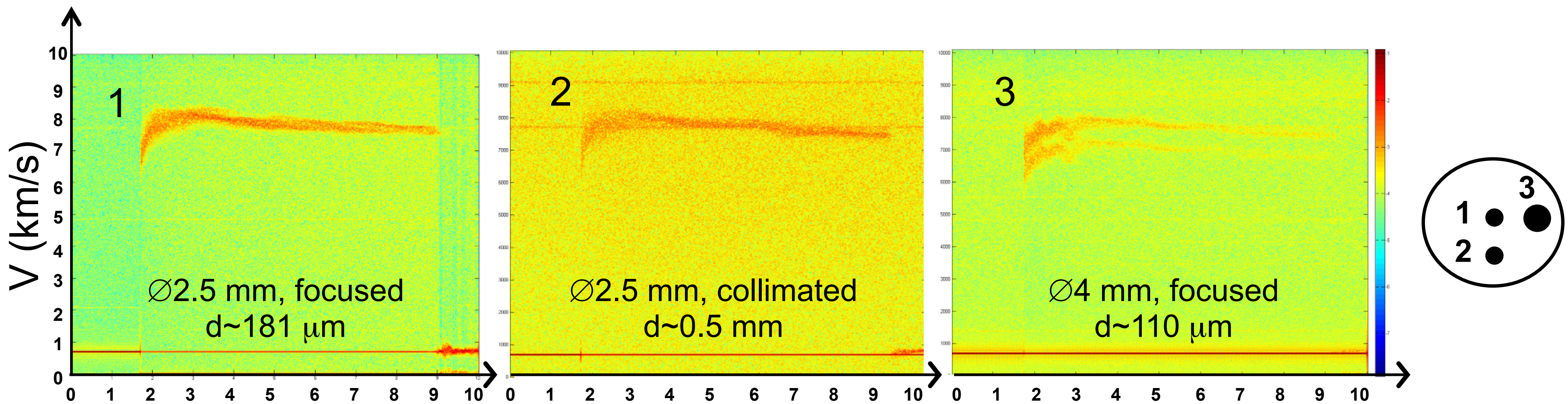
$V_{prods} > D$

PDV results: Influence of the probe

OZ Optics probes with a working distance of 50 mm

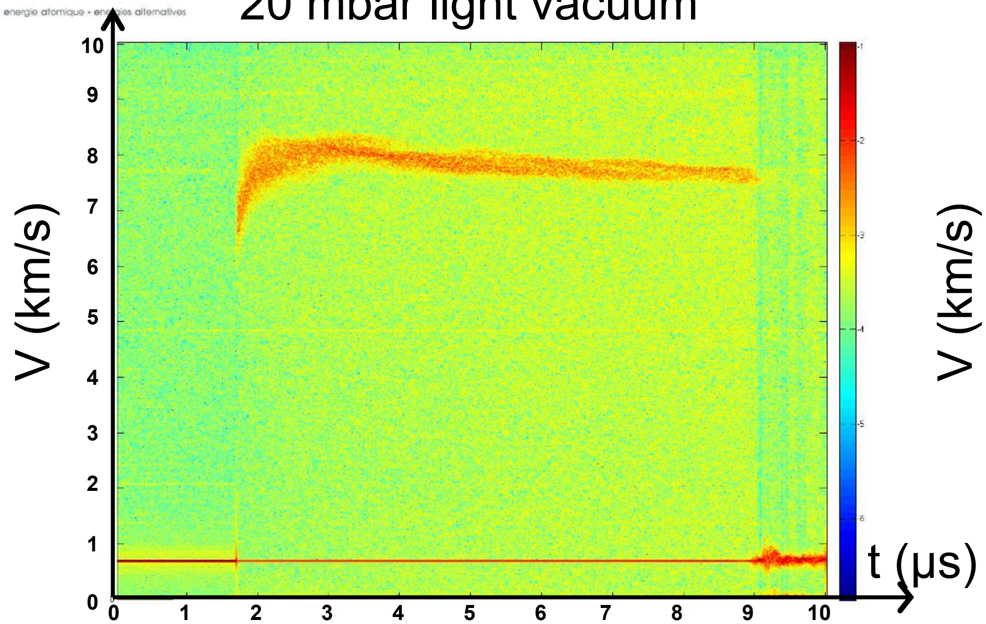


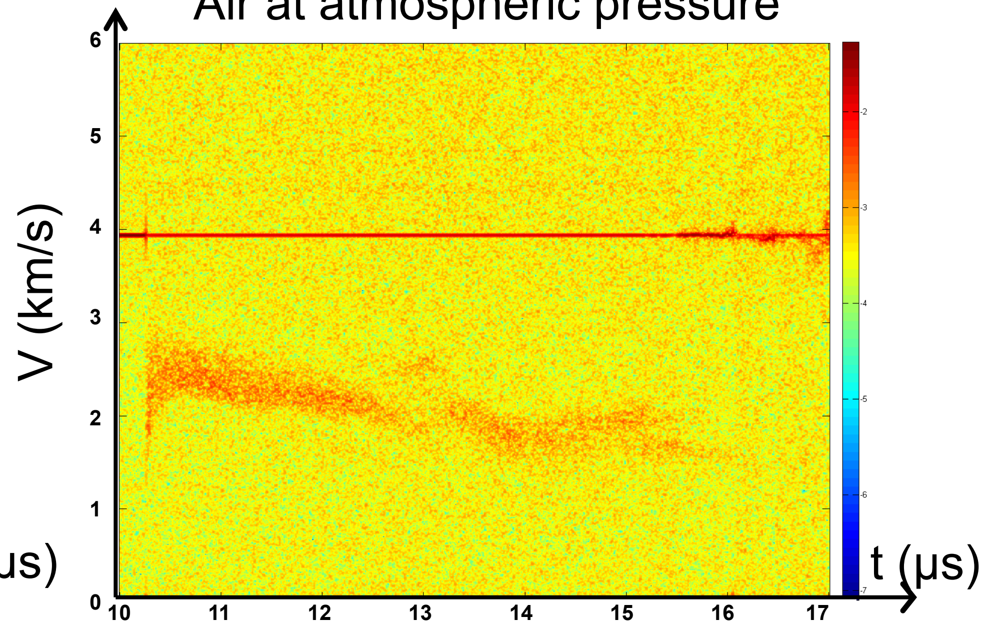
Pivot = -873 m/s, 50 Gs/s sampling, 4 μs record

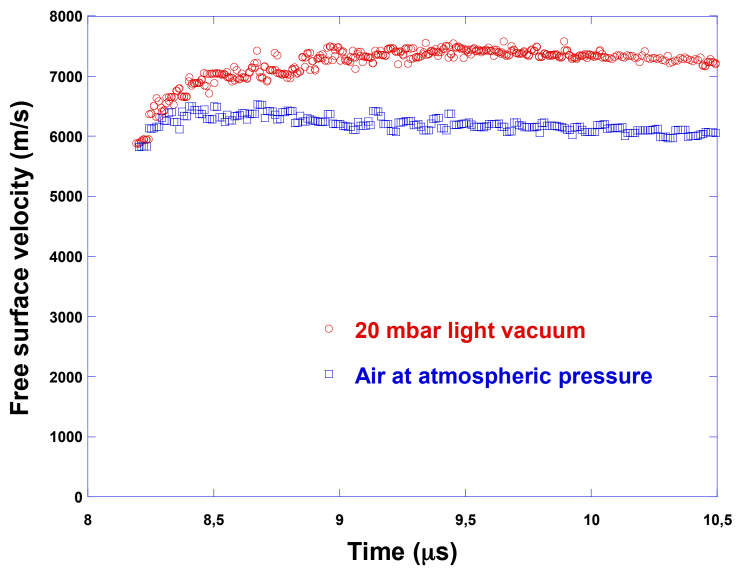


Pivot = -692 m/s, 50 Gs/s sampling, 10 μs record

PDV results: Influence of the surrounding atmosphere



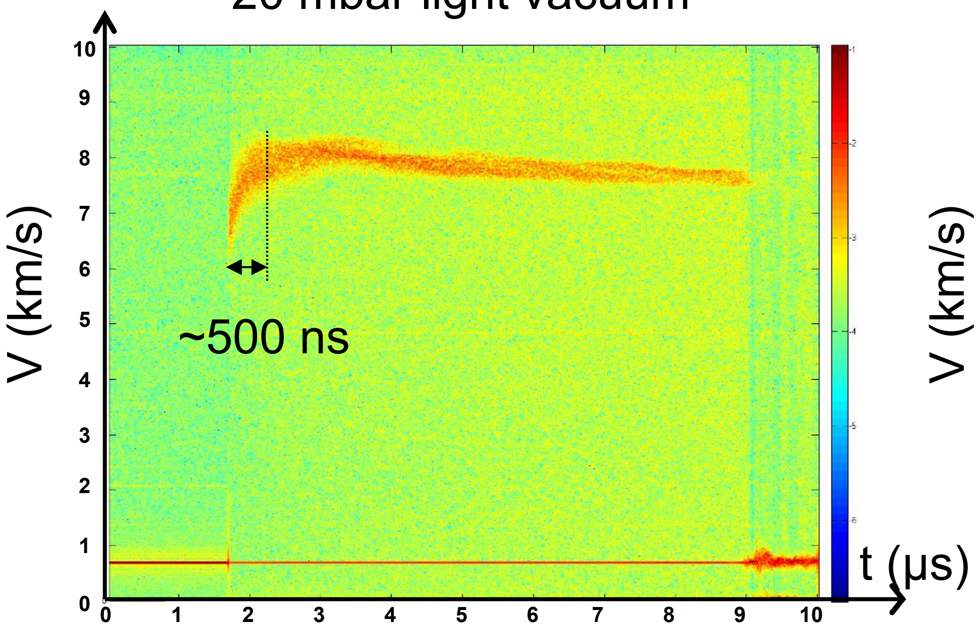




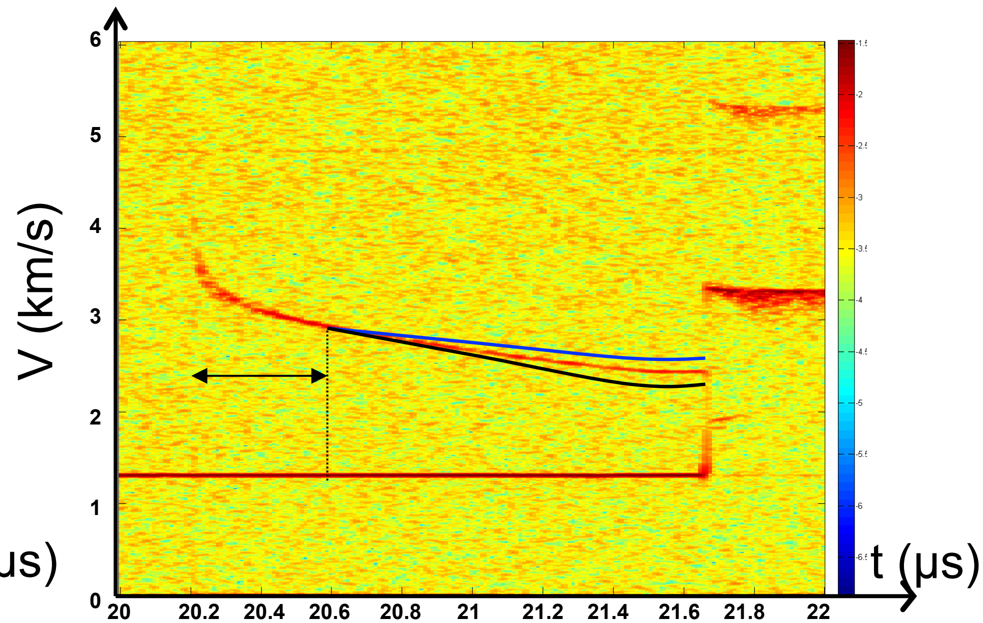
- The initial free surface expansion velocity is similar in both cases (~ 5900 m/s)
- The velocity reaches a maximum (earlier in air) and finally decreases (faster in air than in vacuum)
  - > Interactions between the air molecules and the detonation products
  - > Formation of a shock wave ahead ?

PDV results: Extracted reaction zone parameters

TATB Free surface
20 mbar light vacuum



TATB/LiF interface



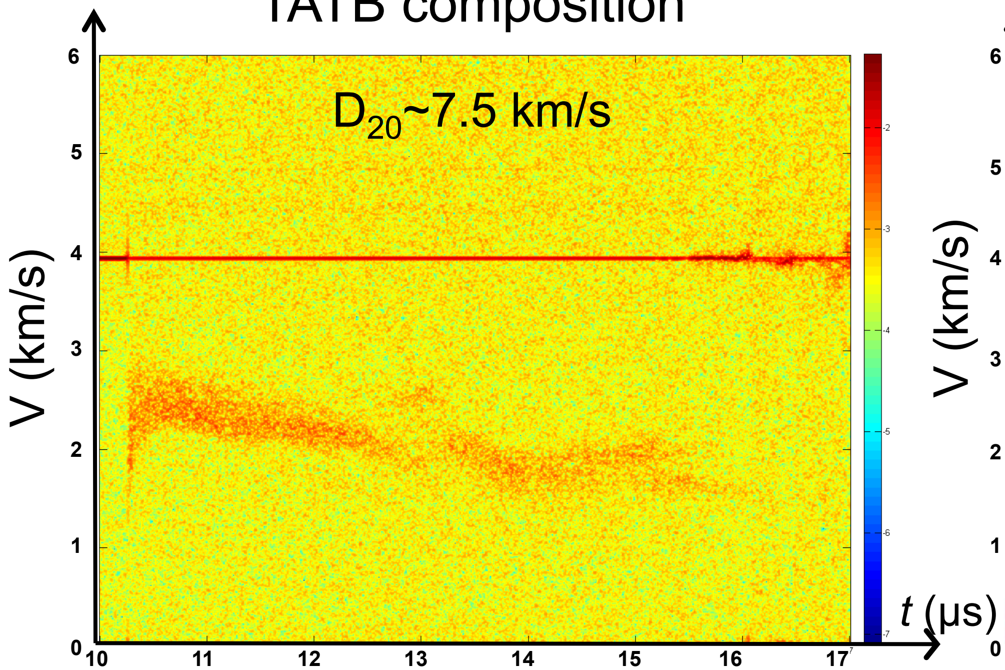
- PDV velocity waveforms exhibit features which can be related to the reaction zone characteristics:
  - ~350-500 ns duration
  - U_{fs}=5900 m/s → $P_{VN}=\rho_0 D U_{fs}/2 \approx 41$ GPa
- Good agreement with previous studies on similar TATB compositions (PBX 9502, LX17)
  - C.M. Tarver *et al.*, J. Appl. Phys. 82, 3771 (1997) → 400 ns
  - S.A. Sheffield *et al.*, J. Chem. Phys. 80, 3831 (1984) → P_{VN}=37.5 GPa

PDV results: Influence of the Carbon content

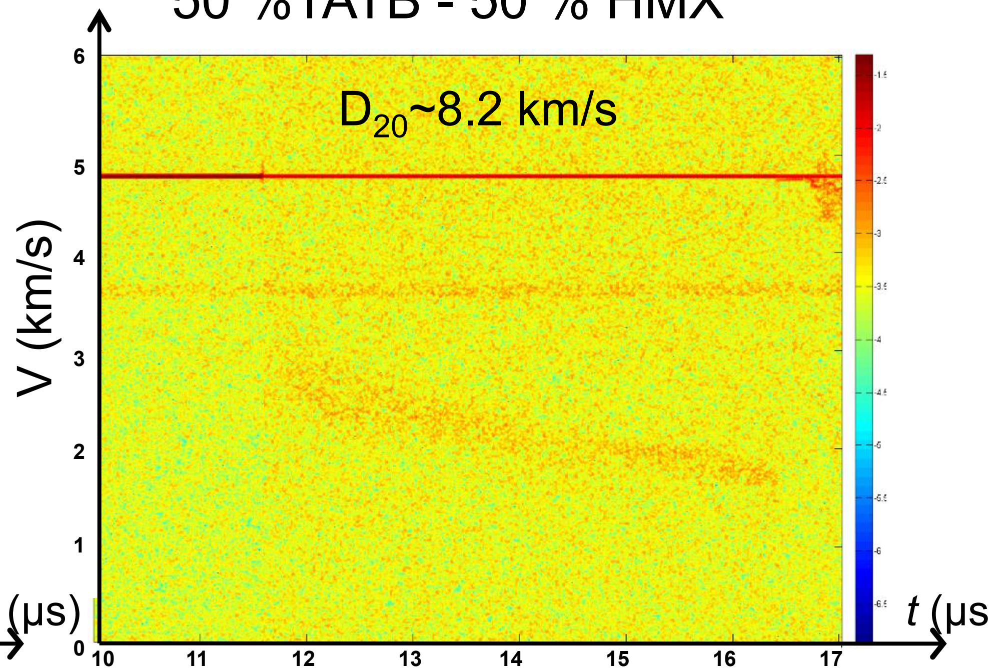
Experiments performed in air at atmospheric pressure

∅=4 mm collimated OZ probe, centerline

TATB composition



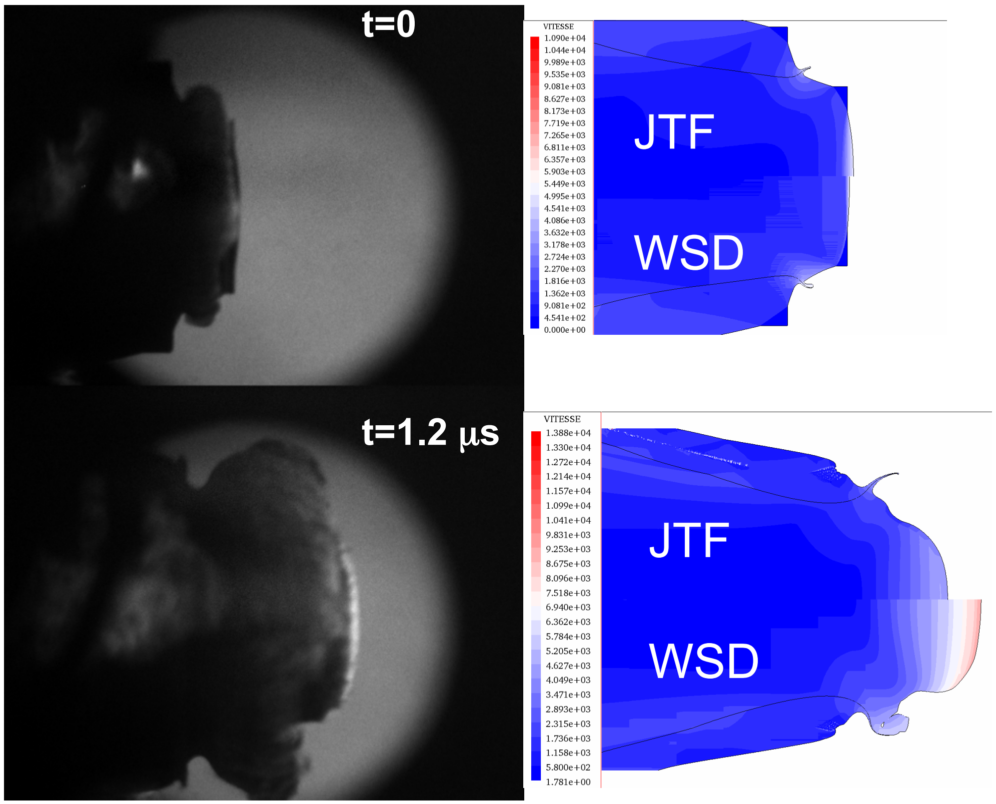
50 %TATB - 50 % HMX

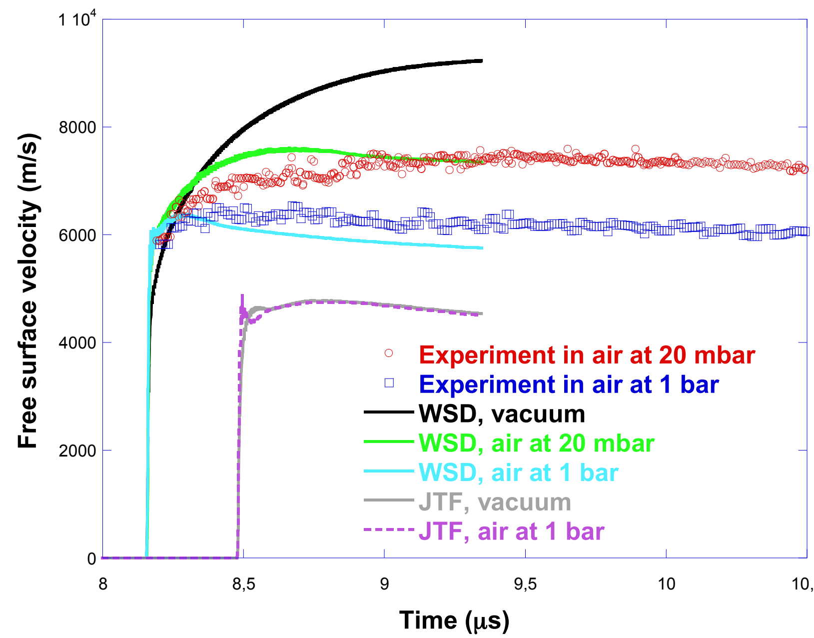


- **A decrease in the carbon content of the detonation products seems to be detrimental to PDV measurements of the free surface of detonating high explosives → lowering of the signal**
- **New tests are planned on a pure HMX composition to check this assumption**

Numerical Simulations

- **2D Eulerian direct numerical simulations with Hesione code, 20 μm mesh size**
  - > **Empirical Hot Spot model (Johnson-Tonks-Forest)**
    - Cochran-Chan inert EOS, JWL EOS for detonation products
  - > **Wide ranging model of Wescott-Scott Stewart-Davis**
    - WSD inert EOS, EOS from CARTE thermochemical code for detonation products





WSD model reproduces qualitatively well both the shape of the cloud of detonation products as it expands into vacuum and the velocity waveforms

Conclusion and perspectives

- PDV measurements have been performed in order to characterize the free surface expansion of the detonation product from detonating TATB sticks
  - > Confirm the abilitiy of PDV to track the expansion of very fast diffuse particles
  - > The initial free surface velocity of the expanding products is lower than the detonation velocity inside the explosive stick
  - > Velocity waveforms exhibit features which can be related to the reaction zone
  - > Significant effect of the surrounding atmosphere (vacuum level)
  - > The carbon content of the detonation products affects the PDV measurement
- We have also performed 2D direct numerical simulations in order to check the ability of various reactive burn models to reproduce our experimental results
  - > Very good results were obtained with the wide ranging equation of state and reactive burn model developped by Wescott, Scott Stewart, and Davis
- Future work:
  - > New experiments with other high explosive compositions (HMX), different surrounding pressures.
  - > Multiple PDV measurements with transverse velocity measurements in order to characterize 2D/3D flows.
  - > New shadowgraphy/schlieren measurements with very short frames (250 ps) taken shortly after the detonation breakout (delay < 500 ns)