ULTRASONIC BULK IMAGING OF SHOCK WAVE PROPAGATION IN OPAQUE SOLIDS

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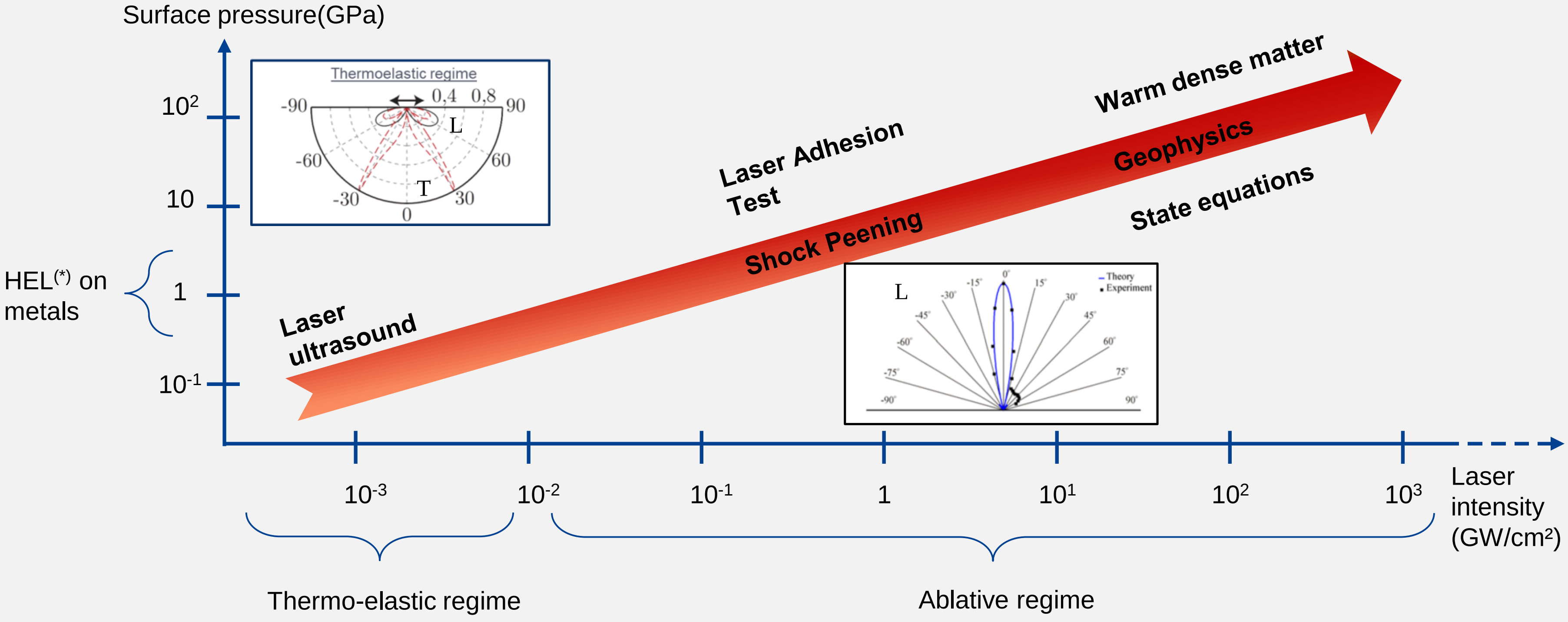
MOTIVATIONS: SEARCH FOR A NEW PROCESS FOR INVESTIGATING SHOCK WAVES

Laser-driven surface pressures (*surface generation*)

Contexte



Laser ultrasound

Shock Peening

Laser Adhesion Test

Warm dense matter

Geophysics

State equations

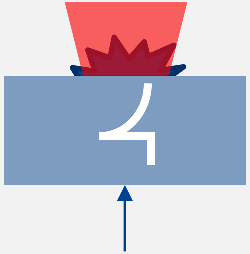
Thermo-elastic regime

Ablative regime

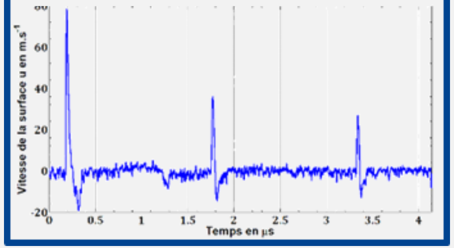
HEL : Hugoniot Elastic Limit

Shock detection at the lab-scale

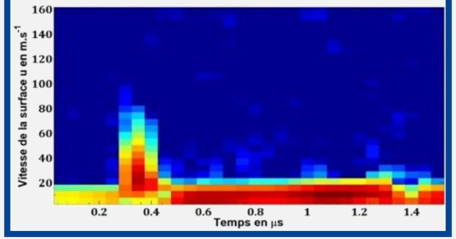
Optical interferometry



Velocity Interferometer System for Any Reflector



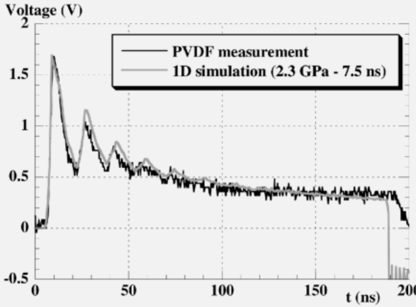
Laser surface velocimetry



🙂
Contact free
Easy to use
Large bandwidth

☹
Surface detection only
Thermal damage can occurs

Gauges PVDF & EMV

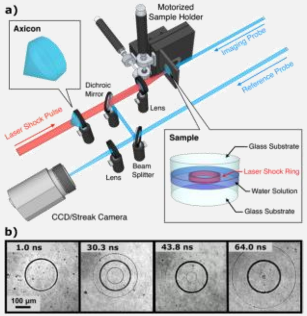


🙂 Easy

☹
Band-pass
Surface detection

Peyre *et al*., J. Phys. D Appl. Phys., (2000)

(Ultrafast) Streak camera



🙂
Both temporal and spatial resolutions

☹
Only for transparent materials

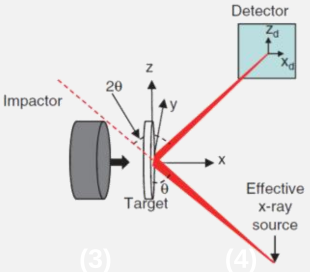
Pezeril *et al*., Phys. Rev. Lett., (2011)

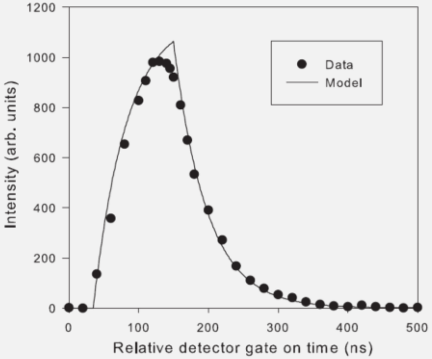
Shock detection on large scale facility

Synchrotron

Advanced Photon Source (APS)

Diameter : 1104 m





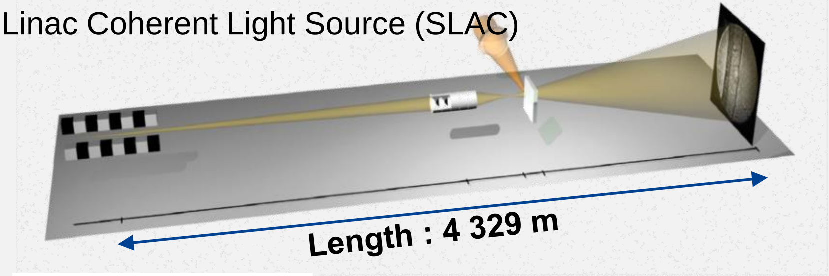
🙂 Bulk detection
Several detection configurations

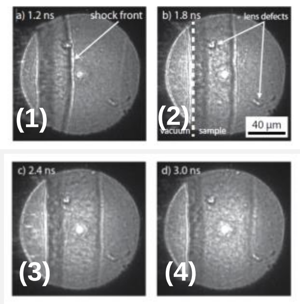
☹ Data interpretation
Beam time

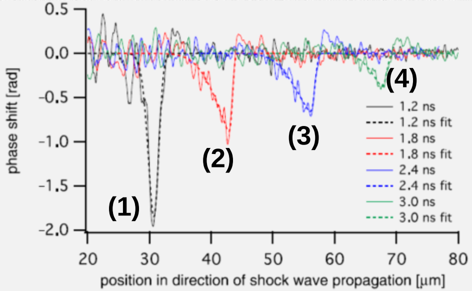
Gupta *et al*., Rev. Scient. Inst., (2012)

X-FEL

Linac Coherent Light Source (SLAC)







🙂 Both spatial and temporal resolution
In situ detection of non-reversible phenomena

☹ Data interpretation
Beam time

Schropp *et al*., Scientic Report, (2015)

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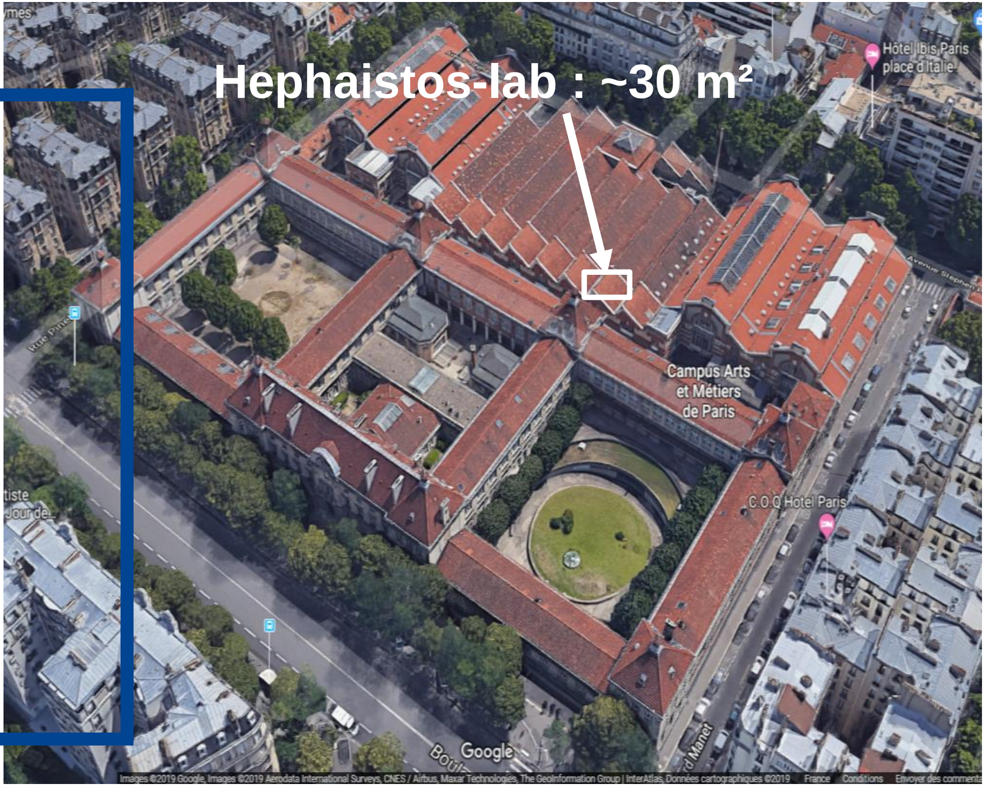
ULTRASONIC IMAGING OF SHOCK WAVE PROPAGATION IN OPAQUE SOLIDS



ENSAM paris

Laser driven shock waves (low regime)

Generation principles

Laser illumination (GW/cm²)

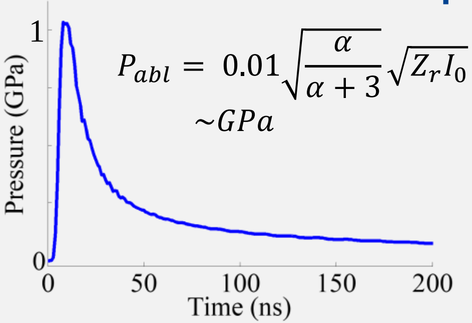
⬇ *Laser/matter interaction*

Dense plasma expansion

⬇ *Action/reaction principle*

Schock wave generation

Ablation pressure



$$P_{abl} = 0.01\sqrt{\frac{\alpha}{\alpha+3}}\sqrt{Z_r I_0}$$

$$\sim GPa$$

Mach number

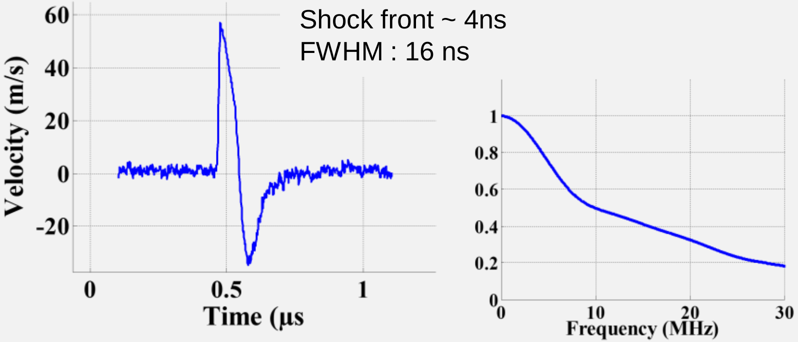
$$M_a \approx \frac{p_a}{\rho_0 c_0^2} \approx 10^{-2}$$

Mach distance

$$L_a \sim mm$$

R. Fabbro et al., J. Appl.Phys., (1990)

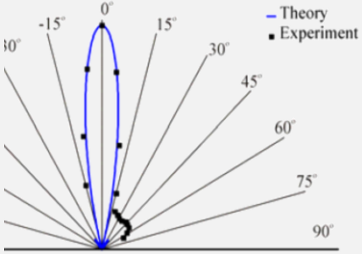
Wave dynamics

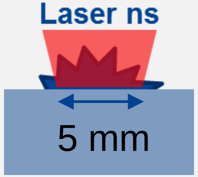


Shock front ~ 4ns
FWHM : 16 ns

Source directivity

Normal direction with respect to the surface

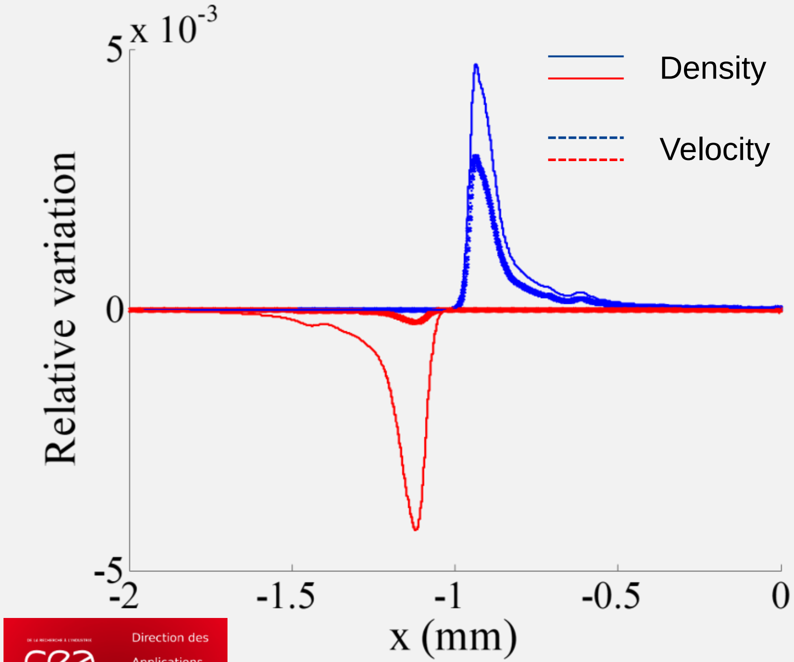




J. Sakamoto *et al*., J. Phys.: Conf. S., (2011)

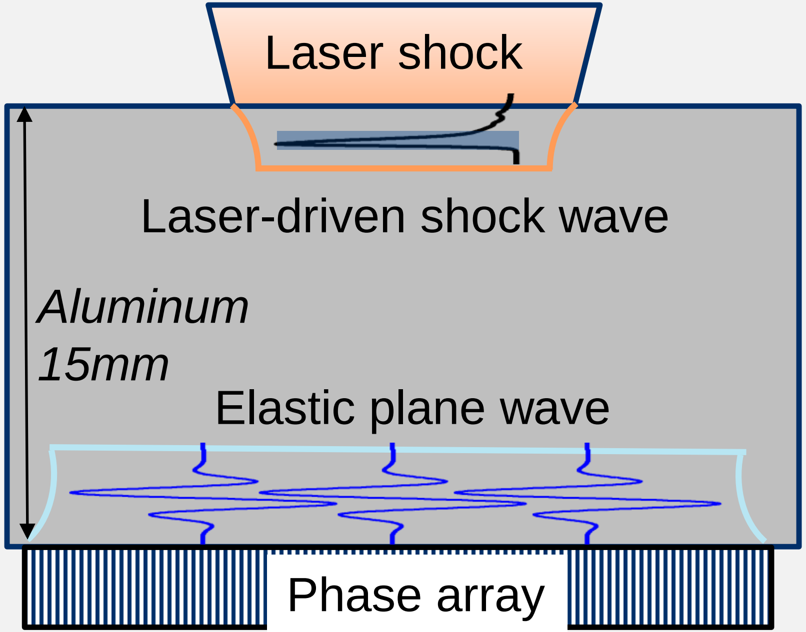
General principles

Shock-driven acoustic impedance variation



Simulations Esther (CEA DAM)

Bulk acoustic imaging of shock propagation ?



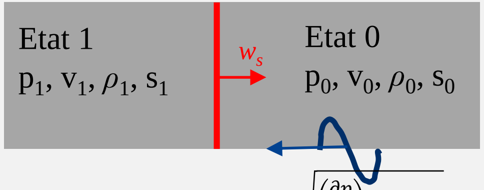
Ducousso et *al.*, Phys. Rev. Applied, **15** (2021)

Interaction between a shock wave and a plane ultrasonic one

Theoretical considerations

- Interaction predicted by J. M. Burgers (1946) et L. Brillouin (1955) …. but never observed
- Can be modeled considering equations of continuity of mass, movement, and entropy, along with Rankine-Hugoniot (RH) jump relations through shocks
- Their resolution gives rise to at least three notable points :

Forbidden reflection



$$c_0 = \sqrt{\left(\frac{\partial p}{\partial \rho}\right)_s (\rho_0, s_0)}$$

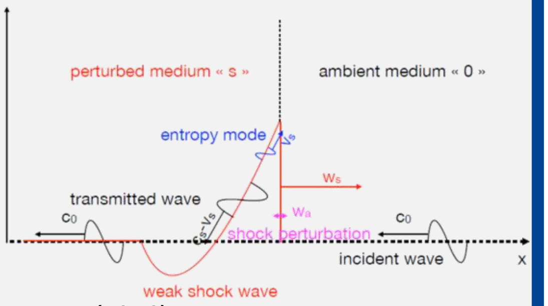
$w_s(t) > c_0$ → *An acoustic plane wave cannot reflect on the shock front*

« accompanying wave »

Brillouin (1955)

Entropy mode

Interaction gives rise to an entropy mode, convected by the upstream flow behind the shock (negligibly small amplitude).



Burgers (1946)

Amplitude

Transmission coefficient of the acoustic wave on the shock depends on several parameters, notably the Mach number and the nonlinear parameters of the materials.

Amplitude of the scattered wave may be greater than the amplitude of the incident wave

McKenzie (1968)

Experimental setup

Laser Hephaïstos (PIMM)

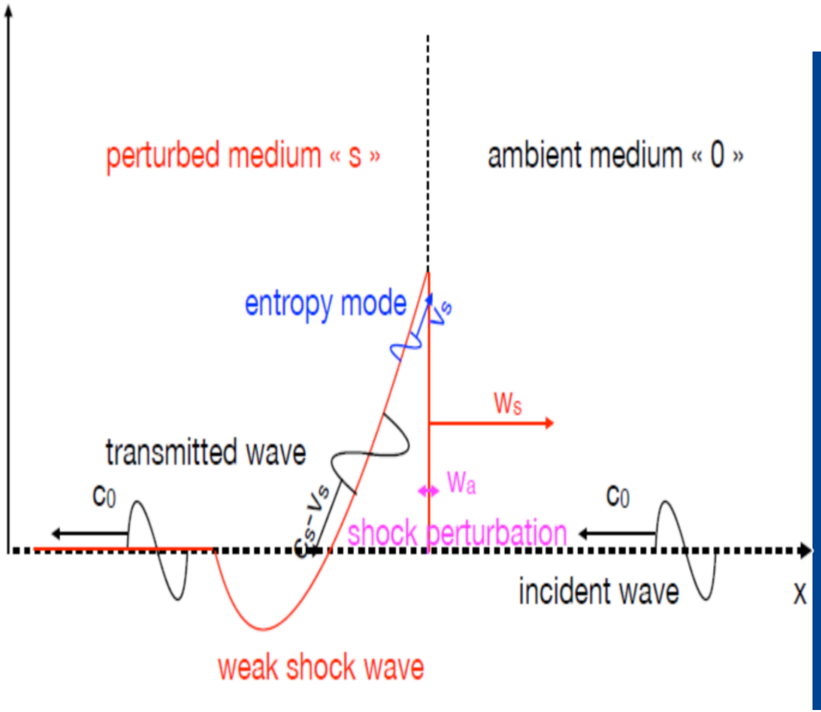
- Laser Thales Gaia HP :
  - 7 J/pulse
  - Repetition rate 2 Hz
  - Wavelength 532 nm
- Fluencies up to 8 GW/cm^2 can easily be reached
- Diffractive optical element ➔ almost perfect circular top-hat profile
- Maximum pressure ~ GPa

Phase array detection

- Phased array driver :
  - 128 voies
  - Band width : 0,7MHz – 20 MHz
- Phased array :
  - 15 MHz
  - Pitch : 0.15 mm
  - 128 elements

Time-delay driver

Ducousso et *al.*, Phys. Rev. Applied, **15** (2021)



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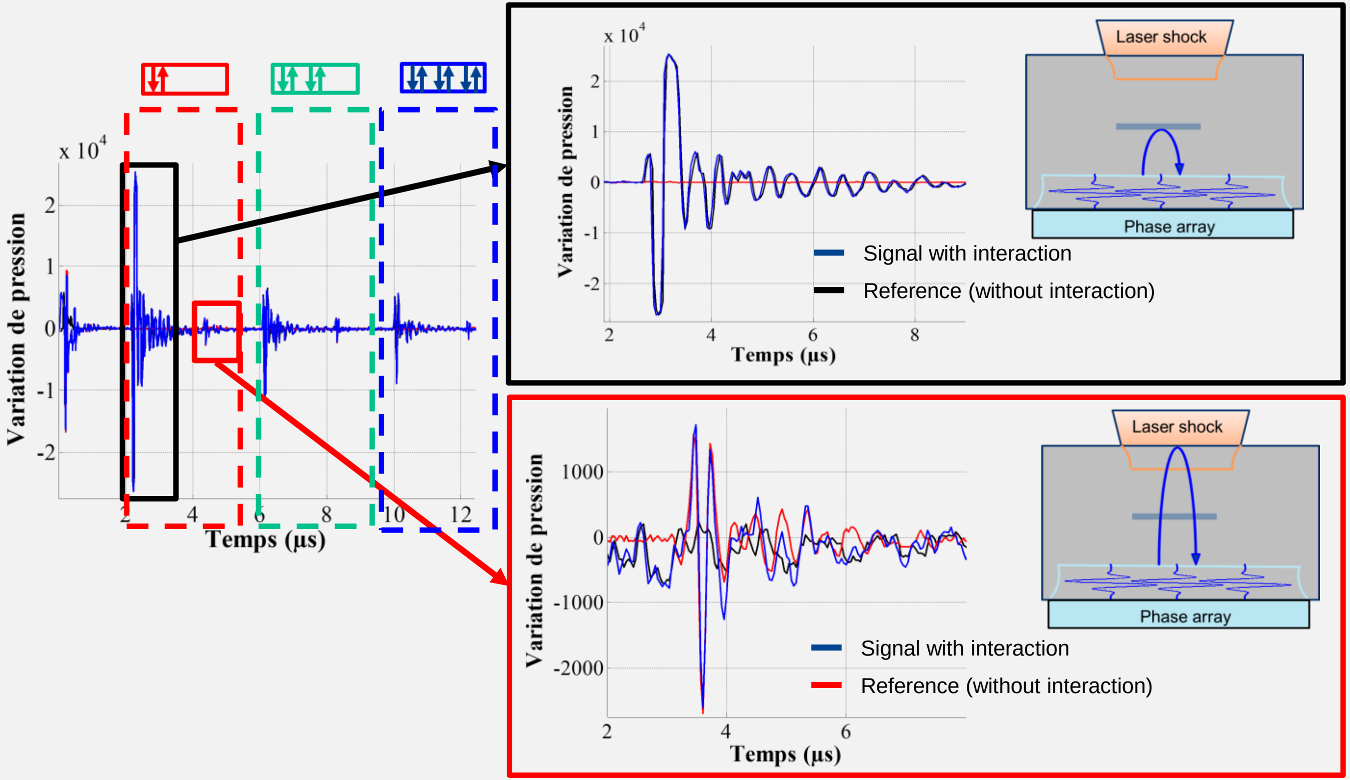
DETECTION OF THE WAVE INTERACTION BETWEEN ACOUSTIC AND SHOCK WAVES

Detection of the interaction between acoustic and shock waves

Détection



How to detect this non linear interaction ?

- Doppler effect?

☹ Band width of the detection

- Relative variation ?

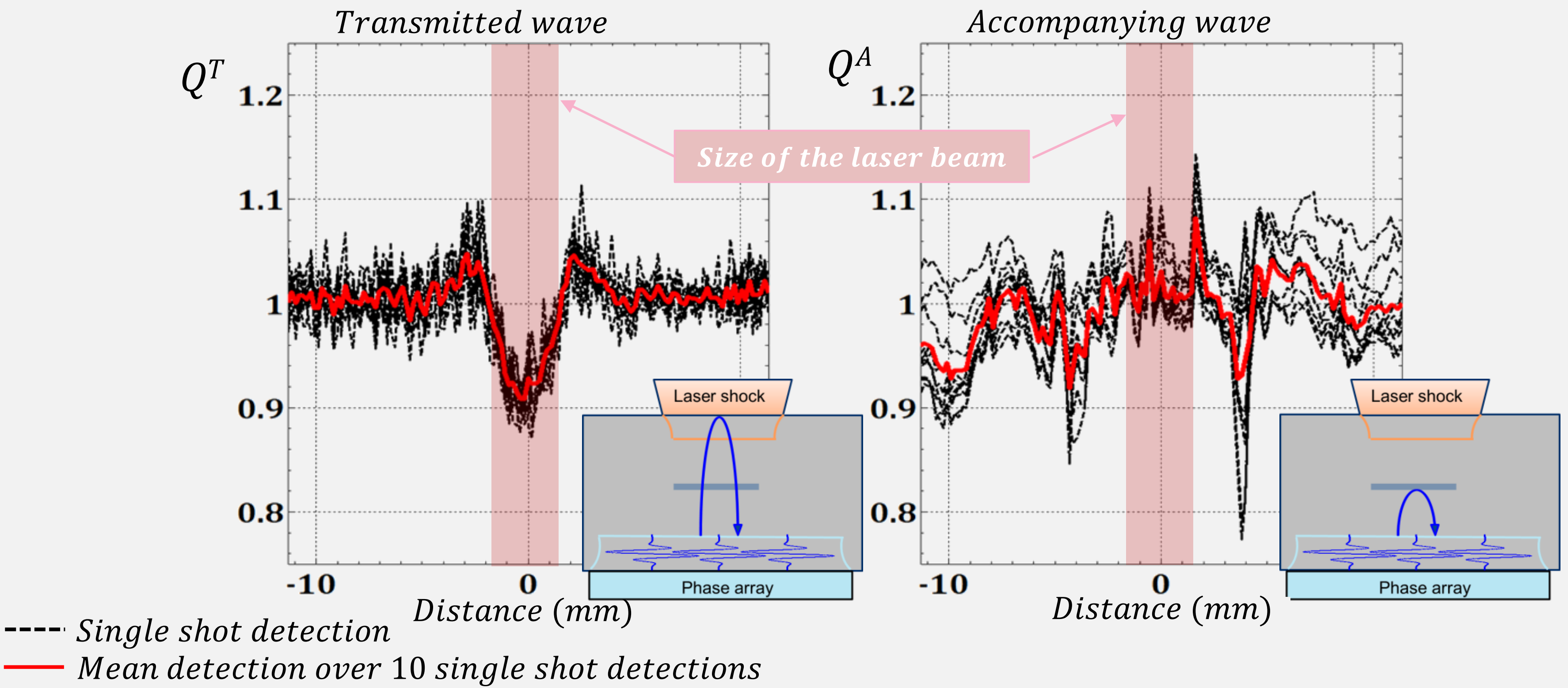
☺

$$Q = \frac{P^h + P^s}{P^h}$$

Interaction between acoustic and shock waves

$$Q = \frac{P^h + P^s}{P^h} = \frac{(homogeneous + perturbed)\,fields}{homogeneous\ field}$$

Détection



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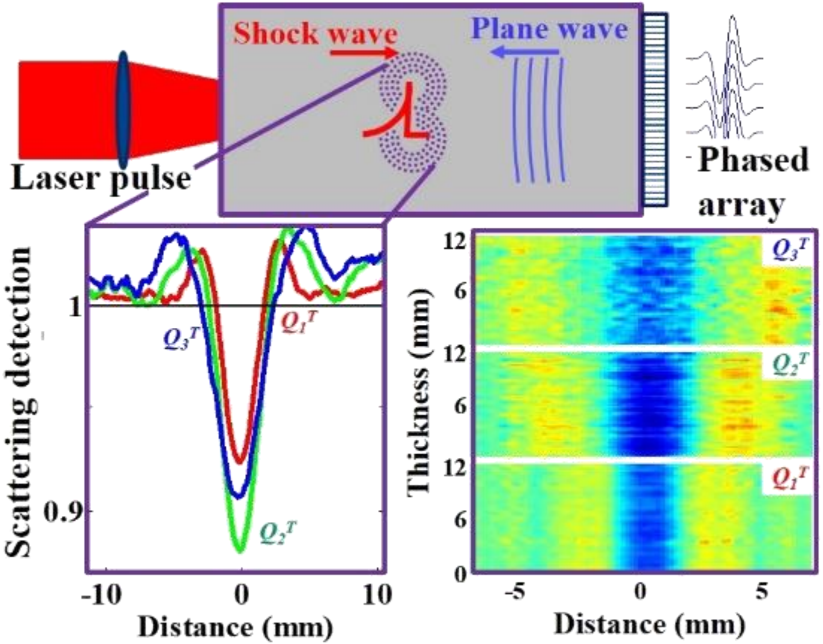
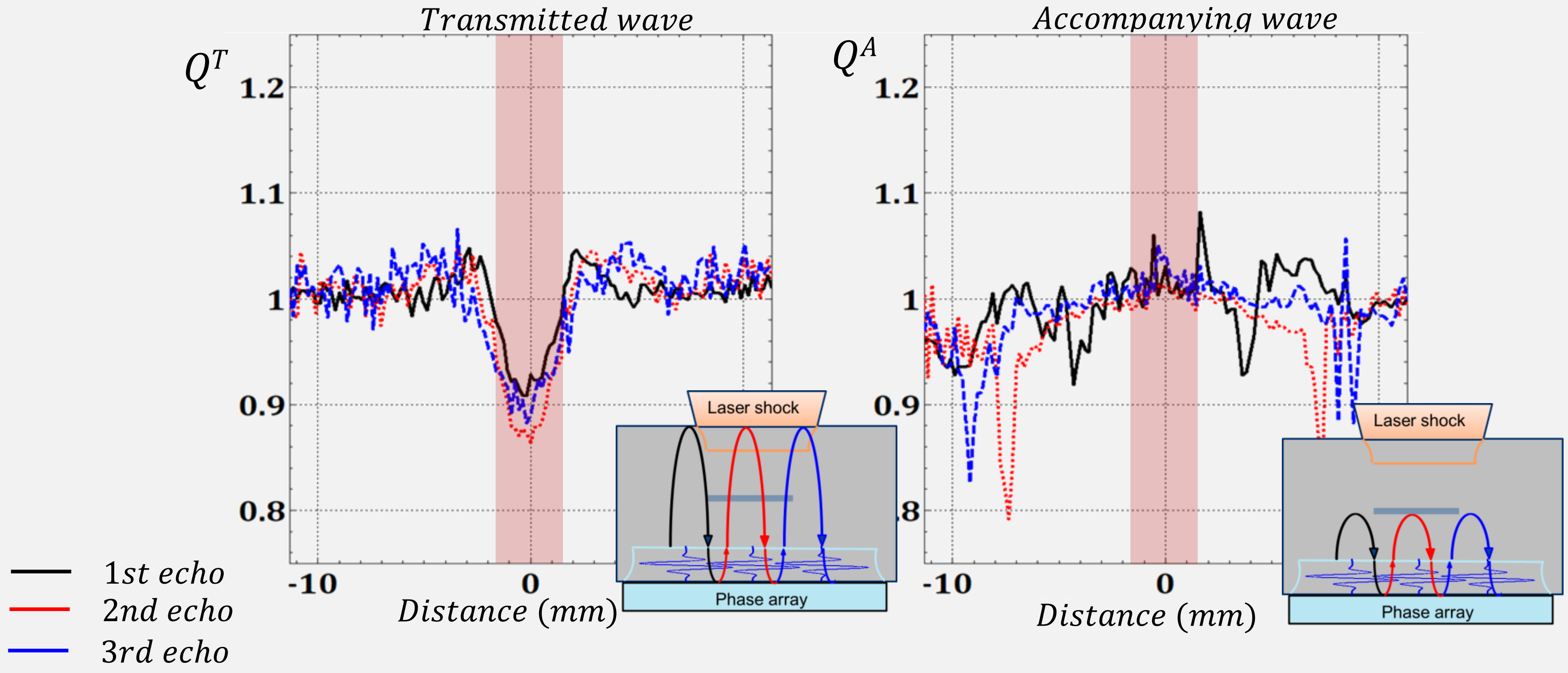
FIRST EXPERIMENTAL RESULTS ON ULTRASONIC SHOCK WAVE IMAGING



First results

Interaction for several back-and-forth travels



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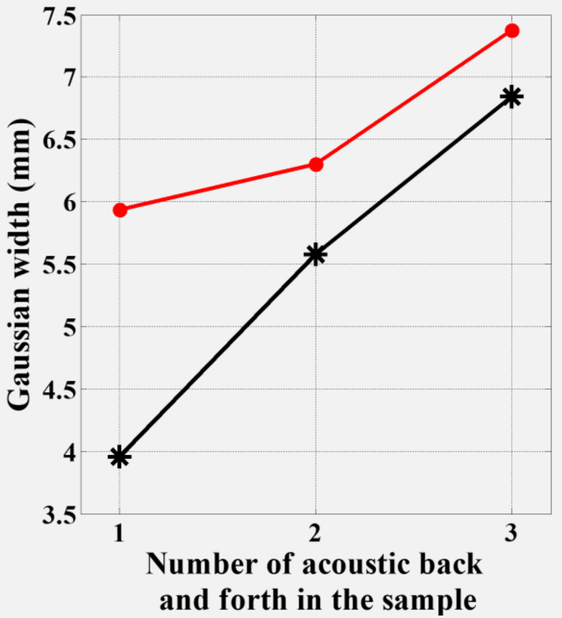
First results

Laser beam size



Laser focusing at :

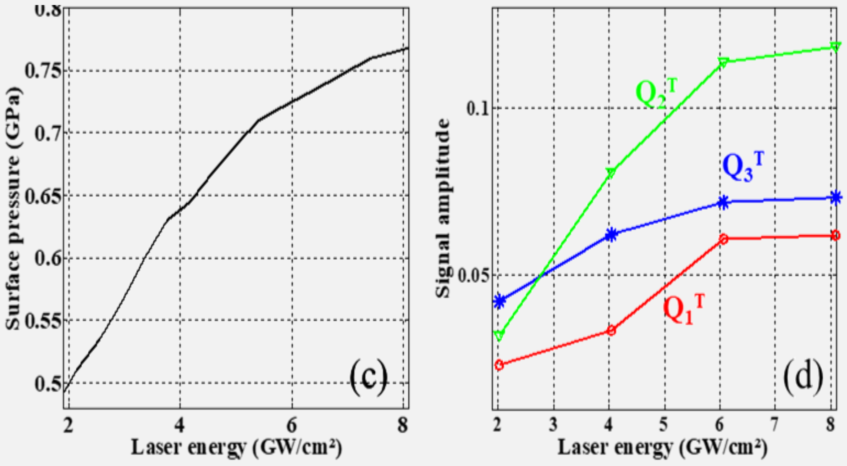
- 3 mm
- 5 mm

Rayleigh distance Z at :

Z = 11 mm
Z = 30 mm

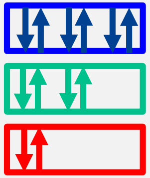
sample thickness : 15 mm

Laser intensity



$$P_{abl} = 0.01\sqrt{\frac{\alpha}{\alpha+3}}\sqrt{Z_r I_0}$$

$$\sim GPa$$



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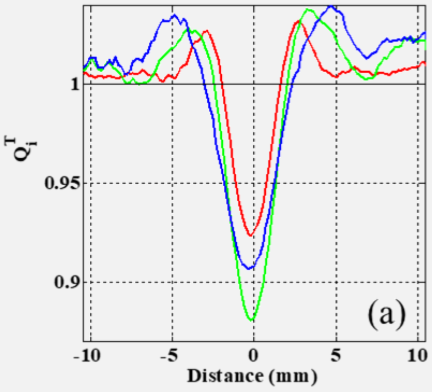
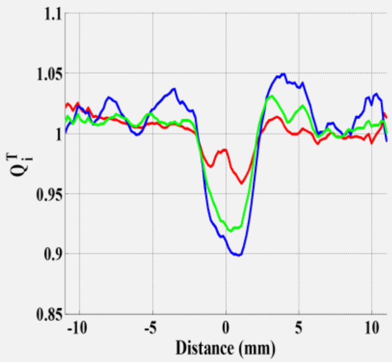
First results

Multi-material analysis

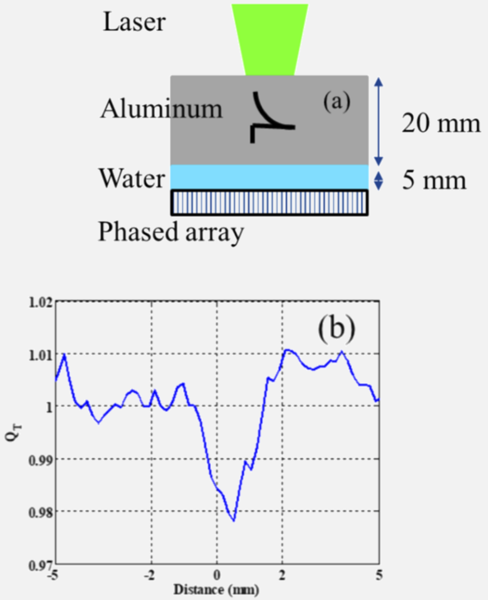
Aluminum



Titanium



Water



🟥 1st echo

⬛ 2nd echo

🟦 3rd echo

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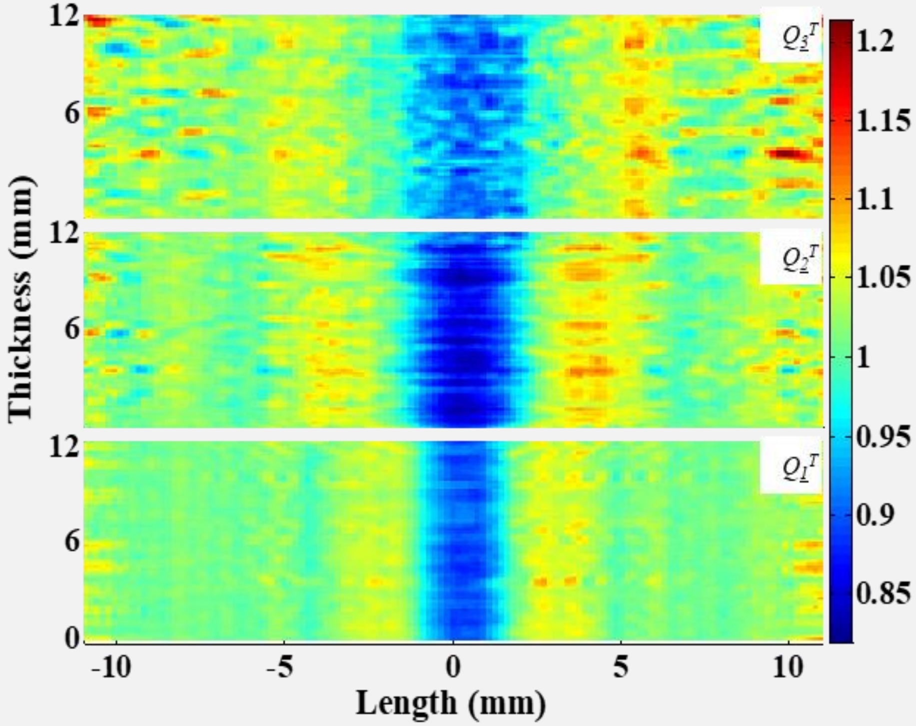
First results

Ultrasonic shock wave imaging

Transmitted wave



3 back and forth

2 back and forth

1 back and forth

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Conclusion

Conclusion

- **To conclude, we have designed an efficient way to monitor longitudinal shock wave propagation using an US probe.**

- **This time-space acoustic monitoring of shock propagation is intrinsically complementary to optics-based detection, from the visible to the X-ray range.**

Futur

- **A numerical model is currently under development**

- **Phase change sensibility demonstration**

- **Other applications include the study of caustics in wave physics or laser-matter interaction and surface strain generation, which could be investigated using surface plane waves**