Dynamic material response under high strain rates: Phase transition dynamics

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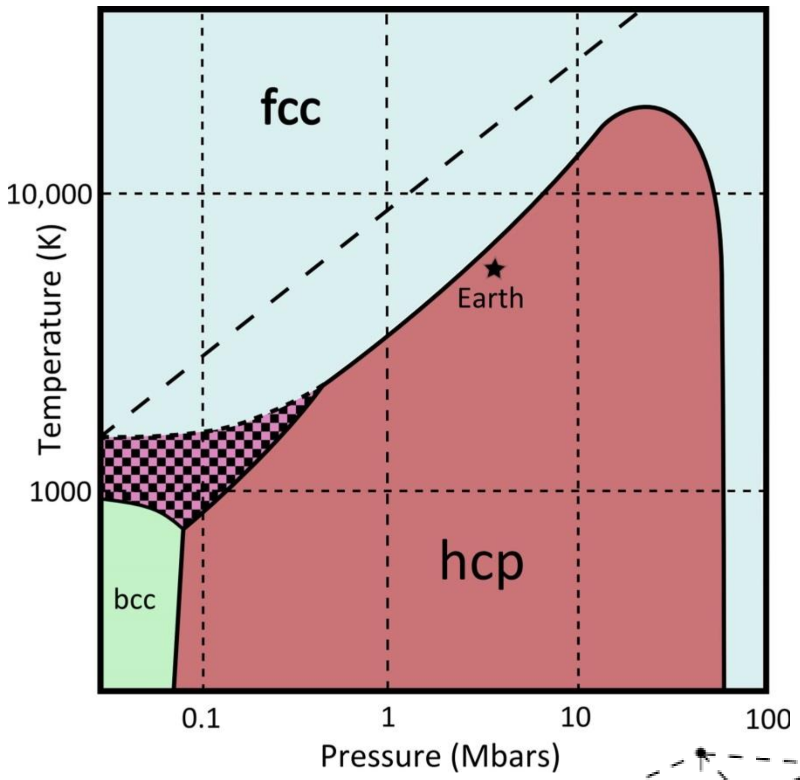
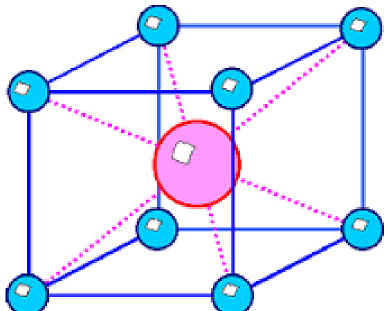
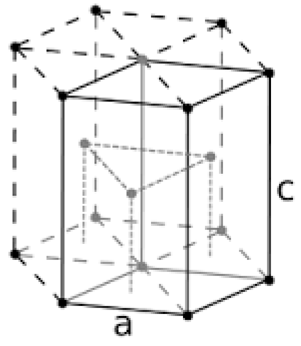
LULI

Iron a-e transition



Transition from body cubic center to hexagonal closed packaged structure at 13 Gpa under static compression
Has been observed under both dynamic and static compression

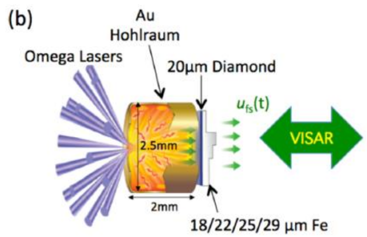


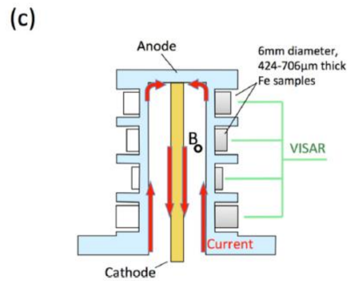


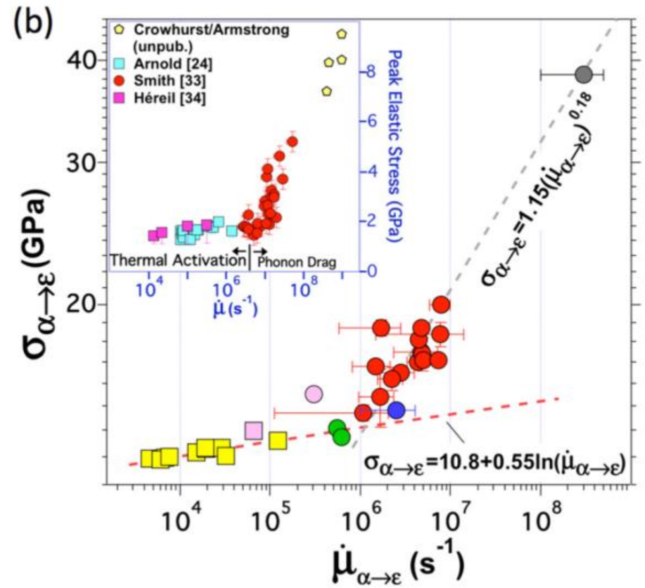
It was highly unlikely that a transition with a change in crystal structure could occur in times as short as a few microseconds.

P. Bridgman (Prix Nobel 1946), Collected papers

Dynamics studies







Magnetic compression

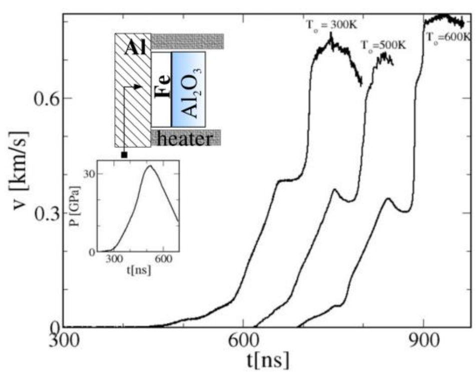
~300 ns, ~500 μ iron

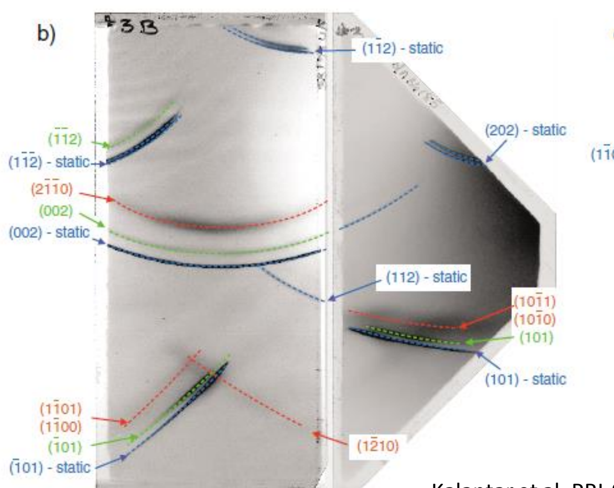
Laser compression

~5 ns, ~10 μm iron

Smith et al, J. Appl. Phys 114, 223507

Bastea et al, Appl. Phys Lett 95, 241911

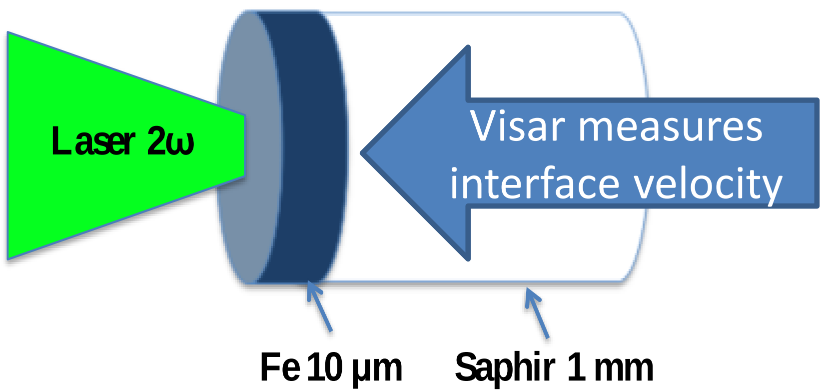


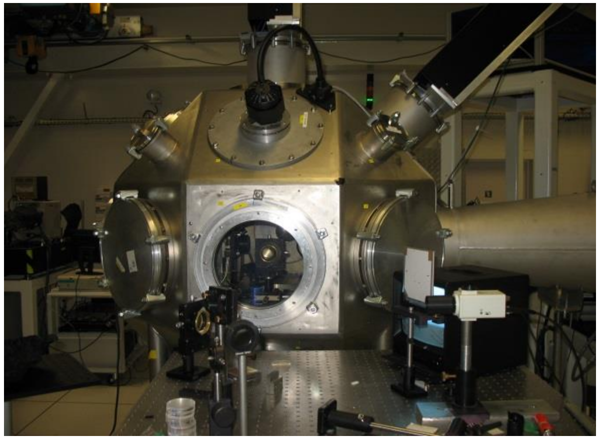


In-situ diffraction of shock compressed iron with laser-driven x-ray source

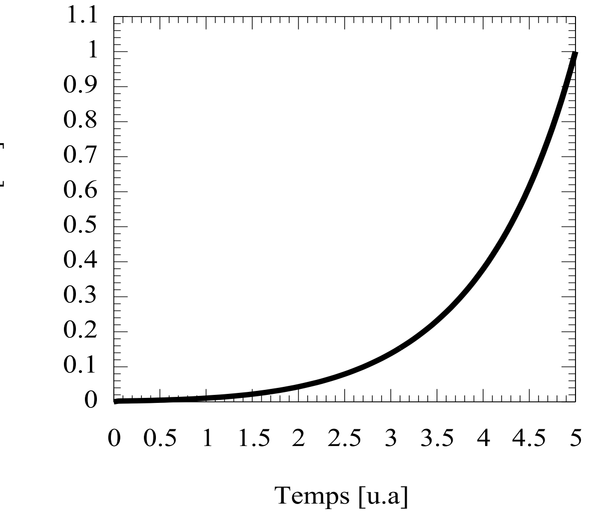
Kalantar et al. PRL 95, 075502

Experimental setup

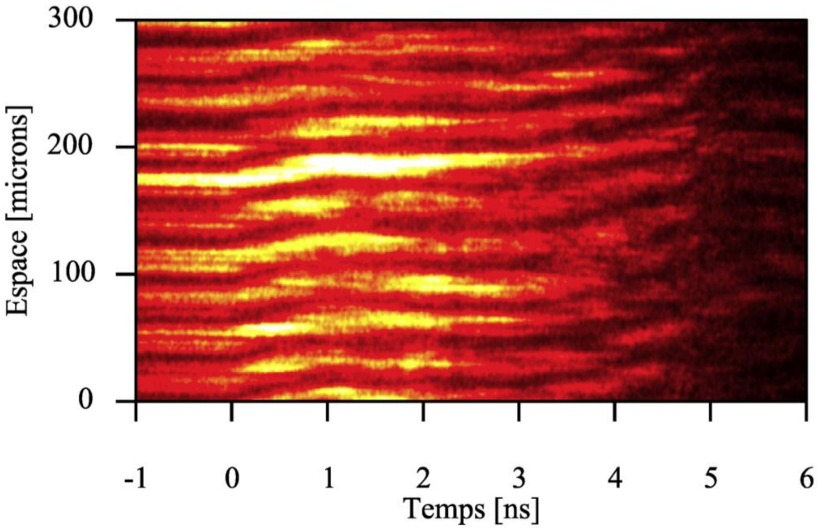




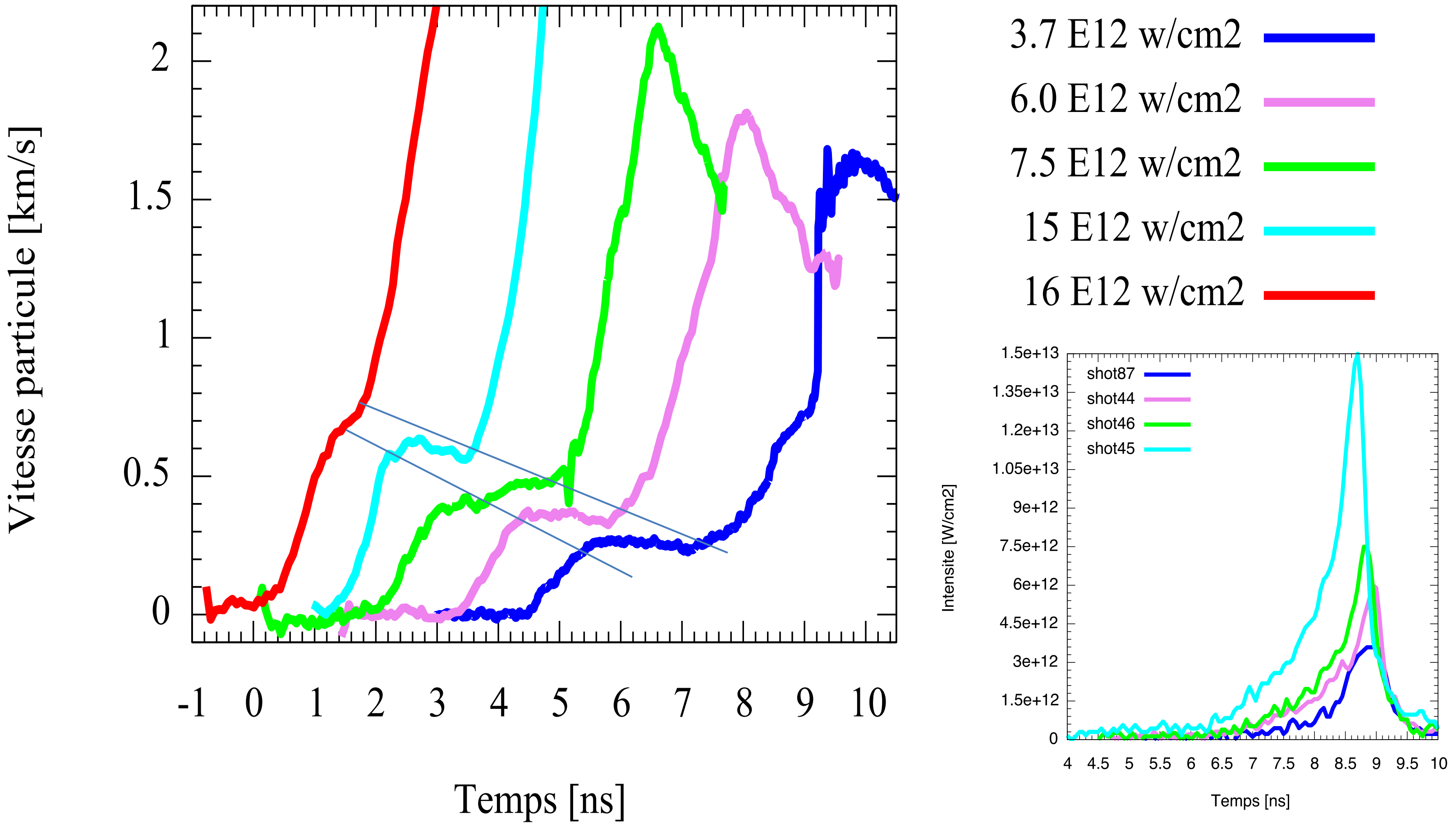
Laser profile



Visar raw data

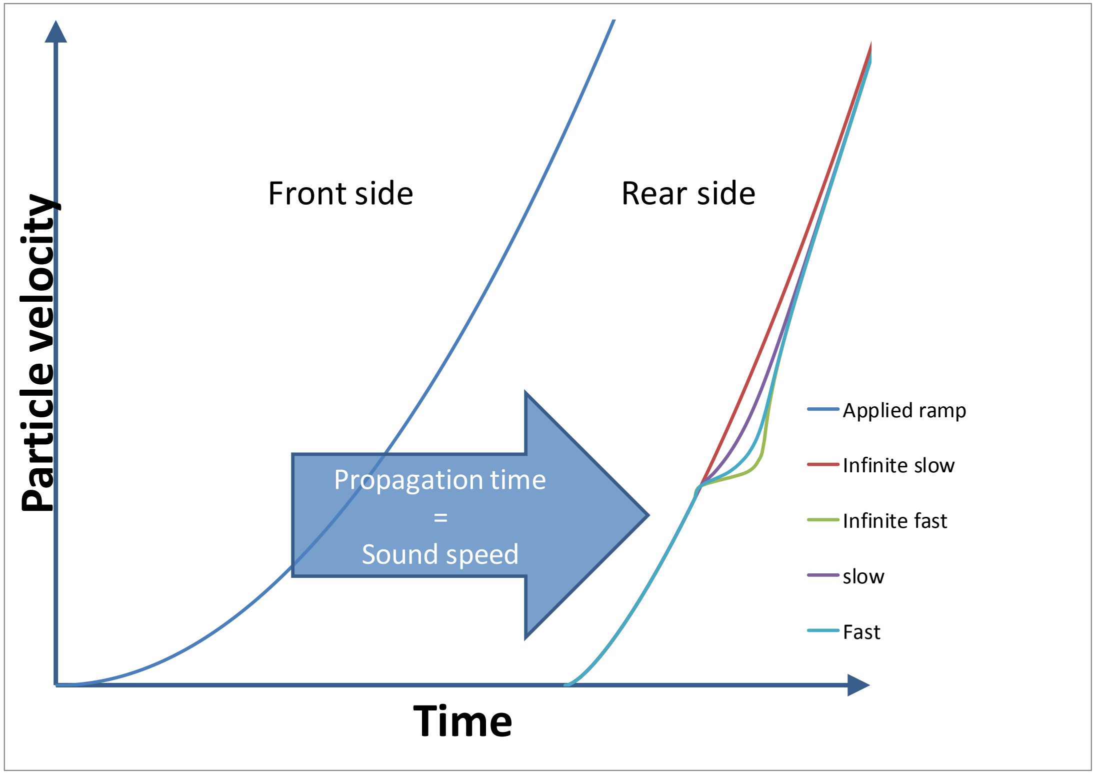


Experimental results



With increasing loading rate, the transition signature moves to higher pressures and the signature gets shorter

Rear surface velocity profiles

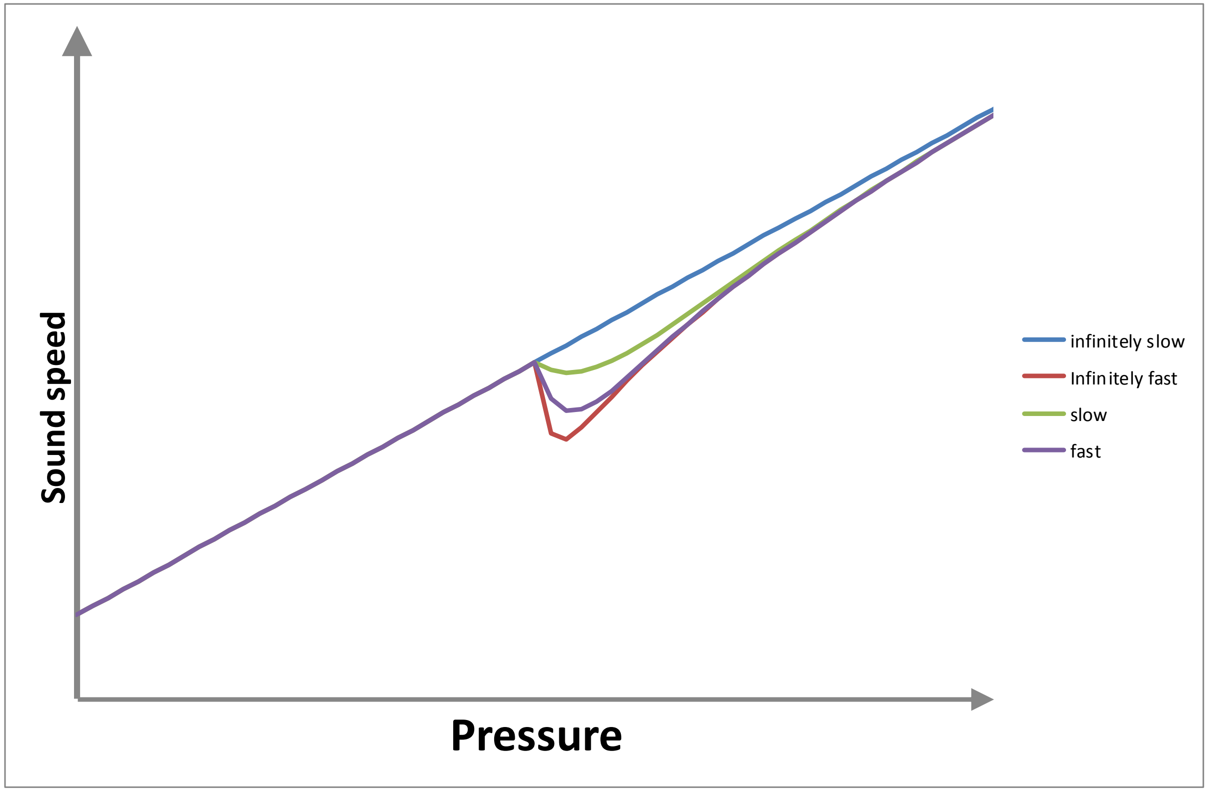


- Obtain sound speed from profiles
- Particle velocity corresponds to pressure
- Length of the profile corresponds to change in sound velocity

Sample needs to be thick enough to separate waves with different sound speeds, but signature is damped while propagating throug target

➢ Good thickness around 10 µm

From sound speed to phase transition



Generally, sound speed increase with pressure

$$\frac{dc_s}{dt} > 0; \sim \frac{dP}{dt}$$

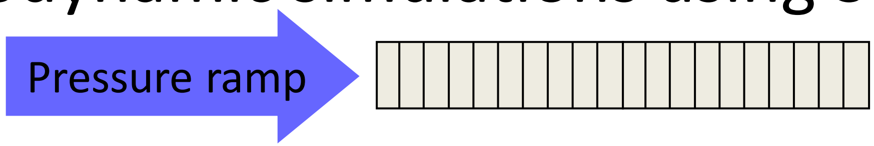
Sound speed decreases at phase transition

$$\frac{dc_s}{dt} < 0; \sim \frac{d(\alpha \to \epsilon)}{dt}$$

The plateau length and pressure depends on the sum of sound speed change by loading rate and phase transition dynamics

Simulation

Hydrodynamic simulations using SHYLAC code



Equation of state for phase 1 (a) and phase 2 (e) with mixing law

$$V = (1 - X)V_1 + X\,V_2 \qquad \mathrm{E} = (1 - \mathrm{X})\mathrm{E}_1 + \mathrm{X}\,\mathrm{E}_2$$

Kinetic model $X(t) = f(\Delta G, \dots)$

Pressure ramp calculated from laser plasma interaction using MULTI code

Two kinetics models tested

Hayes

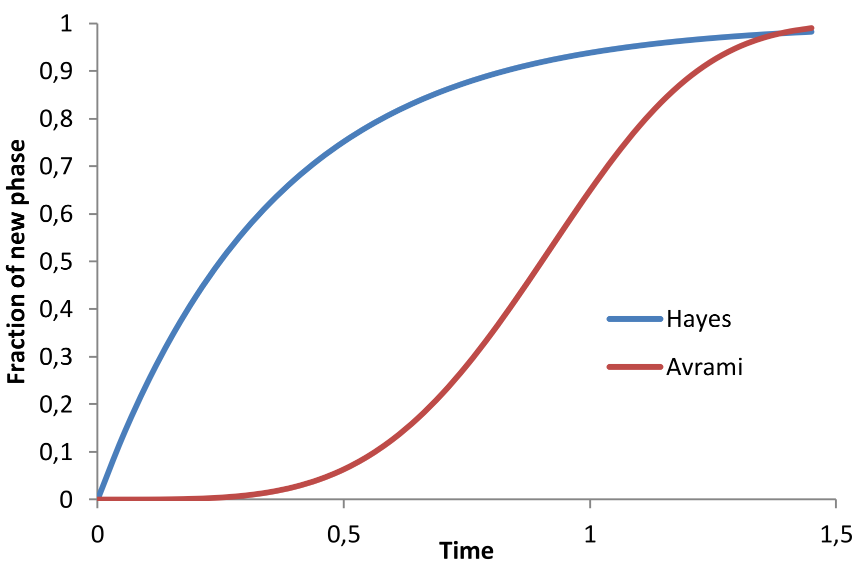
- Transition rate proportional to old phase material and difference in free energie

$$\dot{X}(t) = (1 - X)\, f(\Delta G)$$
$$f(\Delta G) = \tau^{-1}; \alpha \Delta G \ldots$$

Avrami

- Formation of germs of the new phase, which grow at constant velocity

$$X(t) = 1 - exp\left[-\frac{4\,\pi}{12}\left(\frac{t}{\theta}\right)^4\right]$$

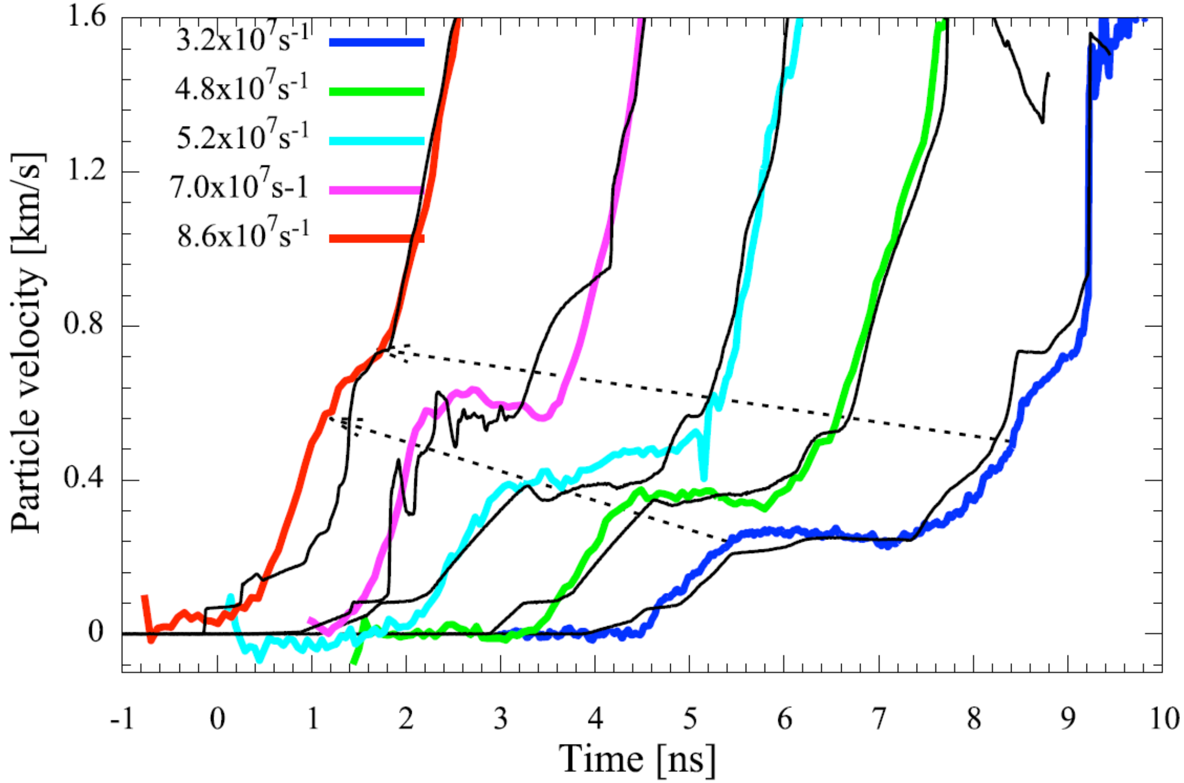


Although the transition time is similar, the models will lead to different plateau pressures and lengths.

A more complicated f(ΔG) can result in a curve similar to Avrami

Smith et al, J. Appl. Phys 114, 223507

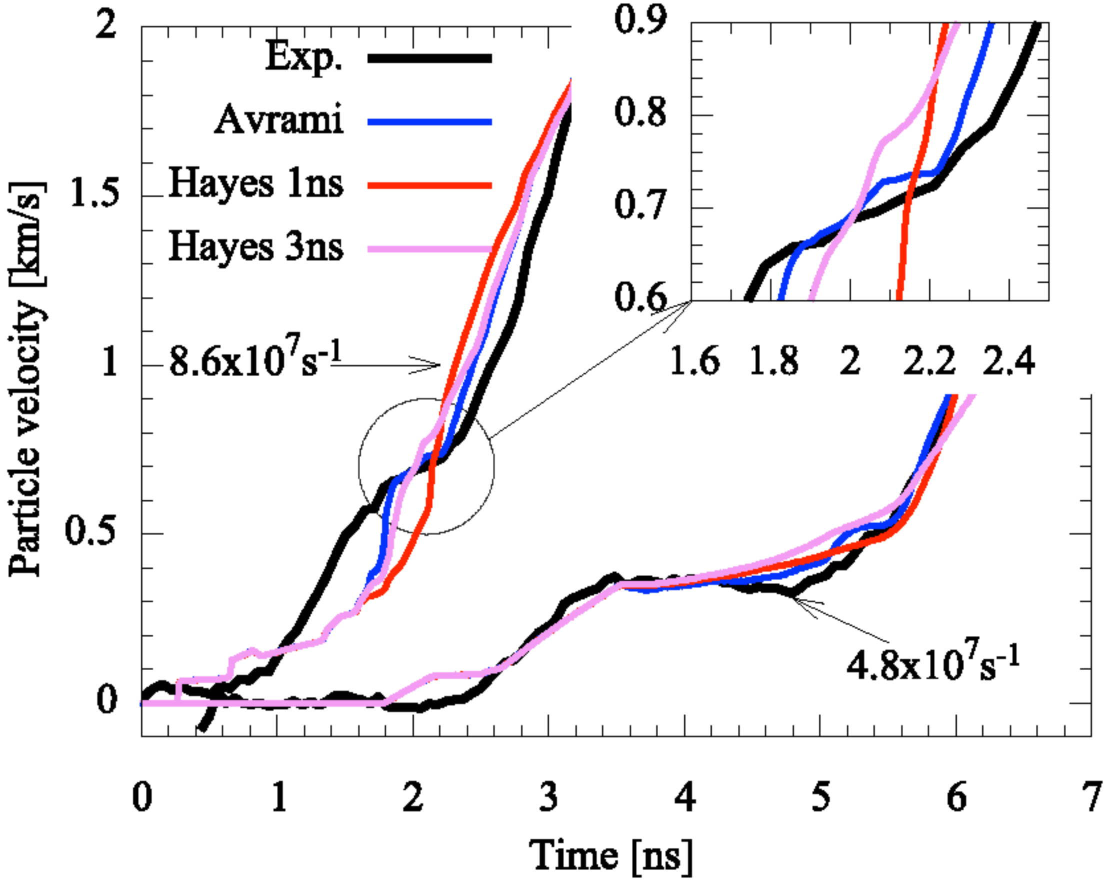
Compare simulation and experiment



Avrami model fits measured profiles for different strain rates with a constant characteristic time θ

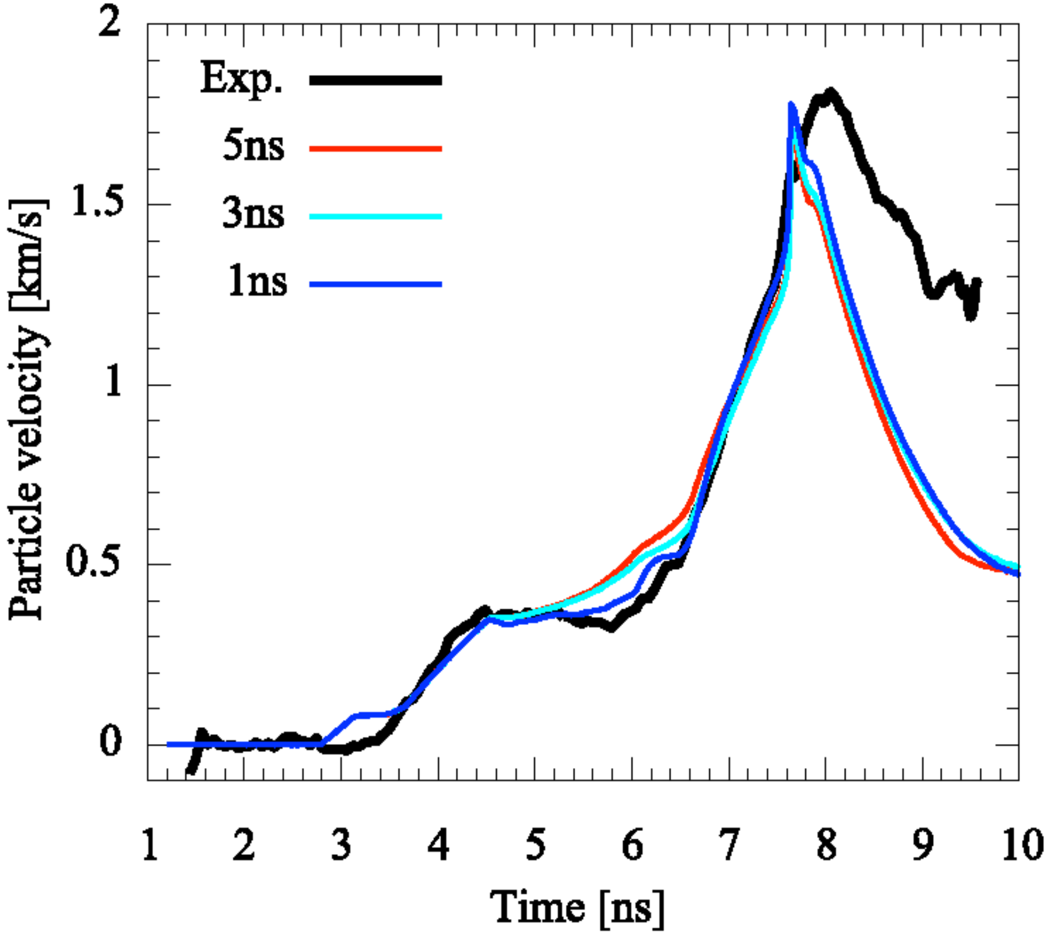
➢ Isocinetic regime

Comparing with Hayes model



Difference between models only at high strain rates significant,
although X(t) is very different

Testing different transition times



1 ns transition time reproduces best the plateau

Open questions

- Studying phase transitions with velocity profiles remains indirect
- Measurements cannot discriminate at low strain rates

➢ Probe phase transition with x-rays
- Temporal resolution ~100 ps
- Possibility for changing strain rates (profiles laser)
- Moderate pressures (100-200 J Laser energy)

Similar applications

- Phase transition studies for dressing/conditioning of material surfaces (A. Zerr): Generation of a superhard layer of high-pressure phase γ-Si_3N_4 on the surface of a bulk piece made of a hard and fracture resistant α- or β-Si_3N_4 forming at 1 atm. We need time-resolved in-situ XRD measurements during shock compression in order to understand whether the transition takes place at all and how γ-Si_3N_4 can be quenched to ambient conditions.

ACO-CHOCOLAS
Matériaux sous Hautes Vitesses de Déformation
Groupe de recherche CNRS

- **Solid Material behaviour**
- **at High Strain Rate (> 10^4 s)**
- **Under shock produced by Laser**

- *From basic science to industrial applications*

- Laser Interaction to produced calibrated shock

- **Material behaviour under shock**

- **Damaging and interface (LASAT)**

- **Material transformation**
- **(LSP-new material)**
-

- Numerical simulations (FEM- DM - DEM)

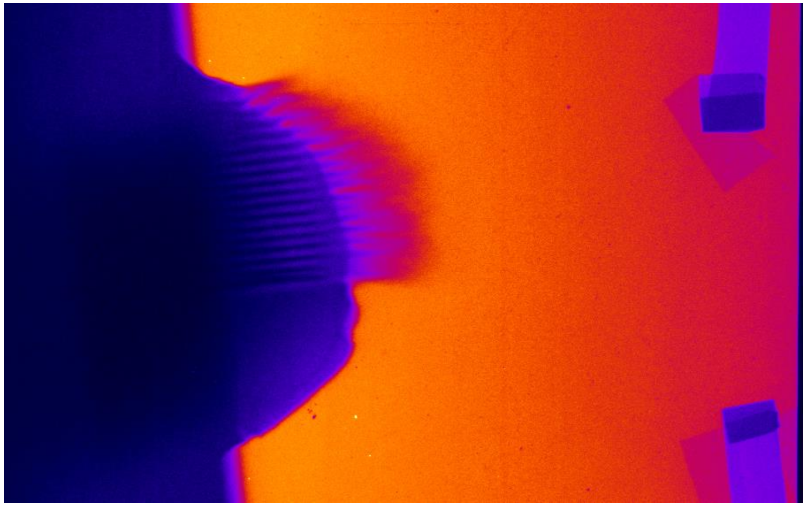
- Diagnostic and experimental methods

ACO-CHOCOLAS

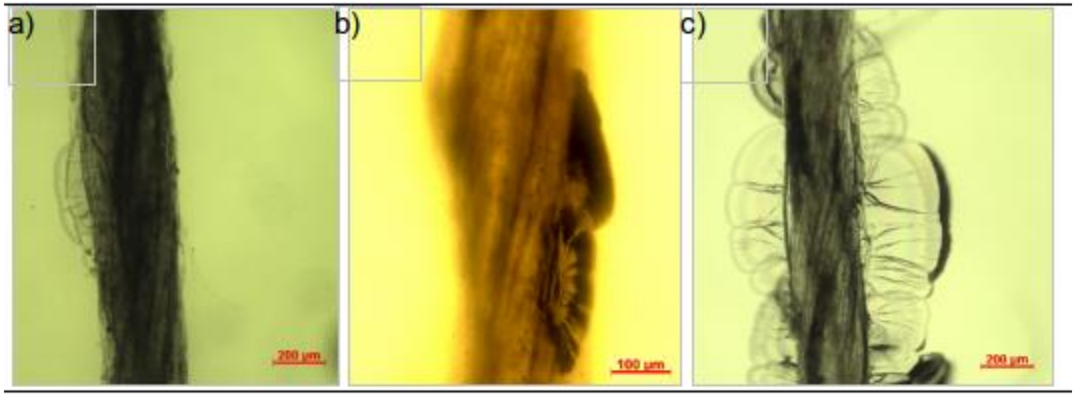
Matériaux sous
Hautes Vitesses de Déformation

Groupe de recherche CNRS

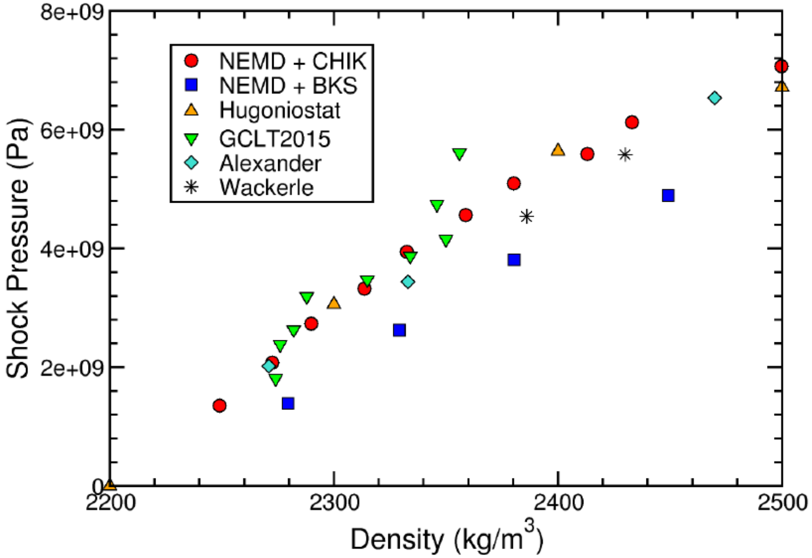
- Micro-jetting (RX-imaging)



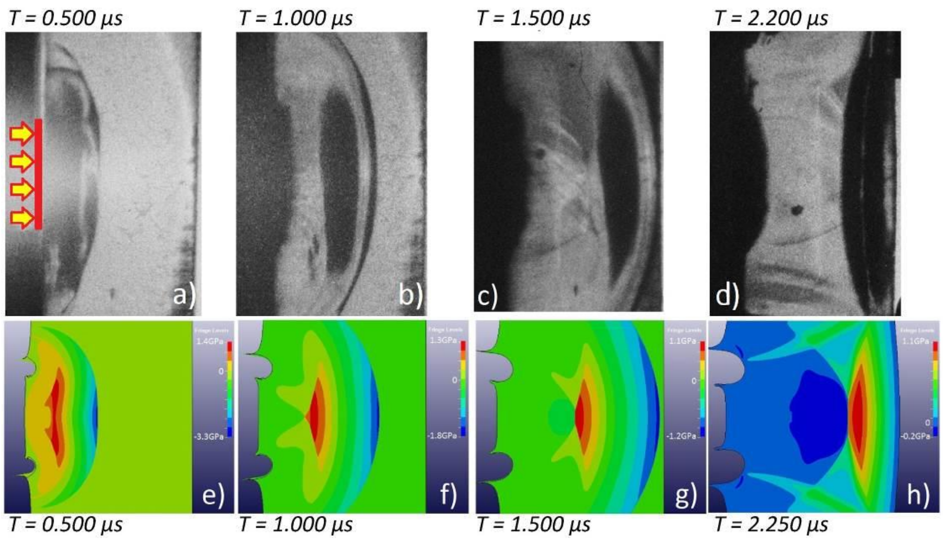
- Bio-composite



- Glass - equation of state



- Polymer under shock (Visible Imaging)



ACO-CHOCOLAS
Matériaux sous
Hautes Vitesses de Déformation
Groupe de recherche CNRS

15 labs

50 researchers 200 publications

Shock Wave and Lasers processes

- PIMM (Paris)
- PPRIME (Futuroscope)
- CEA (Bruyères - Bordeaux)
- LULI (Palaiseau)
- LP3 (Marseille)
- IRDL (Brest)
- **CELIA (Bordeaux)**
- **Hubert Curien (Saint Etienne)**

Spatial-Geology

- CEREGE (Marseille)
- CNES (Toulouse)

Material Sciences and Processes

- IPR (Rennes)
- LP3 (Marseille)
- PIMM (Paris)
- PPRIME (Futuroscope)
- CEA (Bordeaux - Bruyères)
- ECAM (Rennes)
- ICB-LERMPS (Belfort)
- CdM Mines (Evry)
- **ESRF (grenoble)**

Simulation (From DM to FE)

- I2M (Bordeaux)
- CEA (Bruyères)
- Cermics (Marne la Vallée)

Conclusion

- Laser ramp compression a valuable tool to study phase transition dynamics
- Studies on iron suggest Avrami type phase transition with a characteristic time of 1 ns
- In-situ x-ray diagnostics are necessary to better constain differen models

Coworkers

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