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Mesoscale simulations of melt production in porous metals under shock compression

PRESENTED BY

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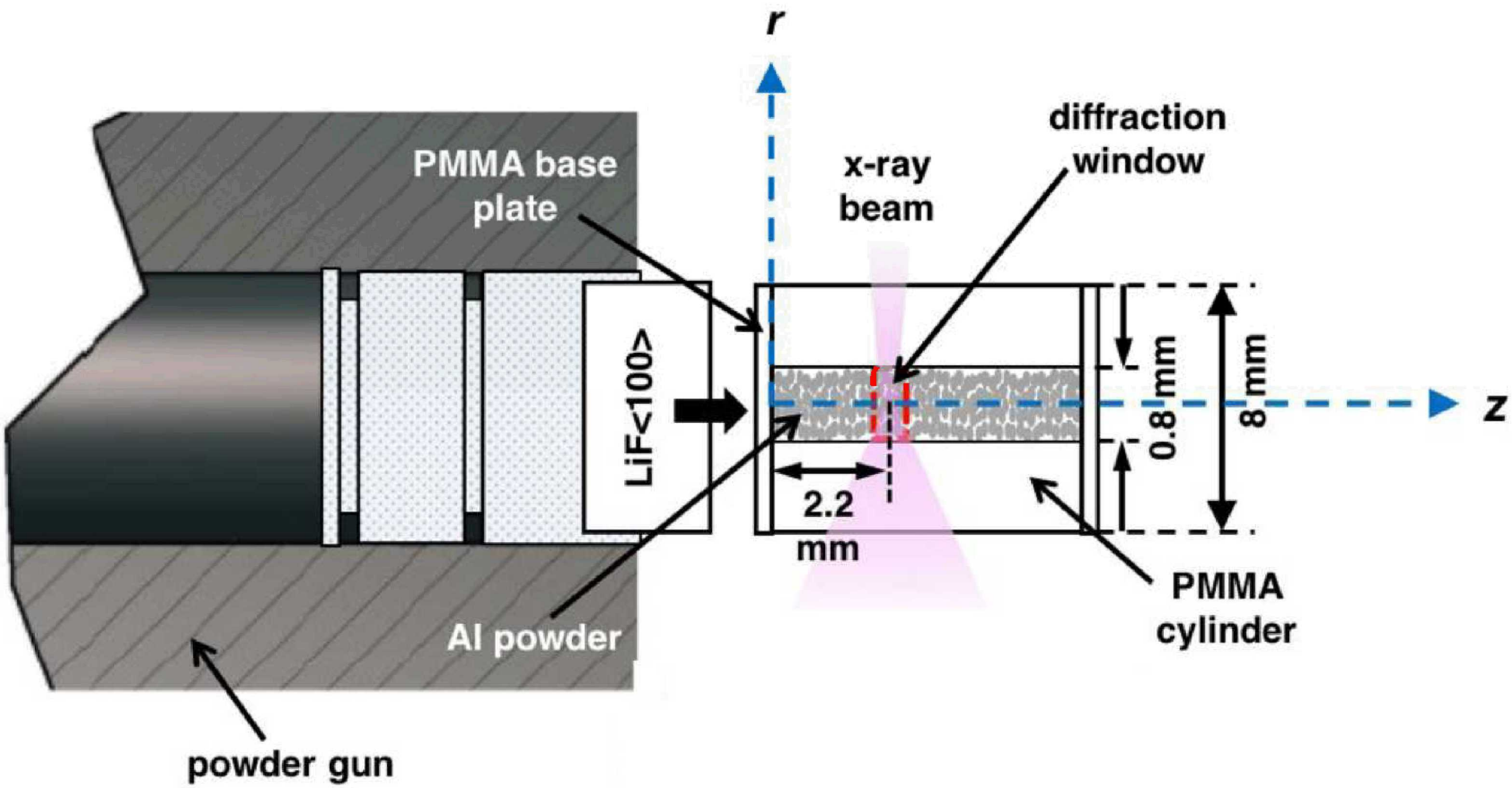
Melting of porous solids under shock loading

- Porous solids undergo melting at much lower shock intensities than nonporous solids
  - Heat generated through plastic work from removal of porosity
  - Melting stress for 60%-dense aluminum ~10 GPa vs. >100 GPa for solid aluminum
- Recent *in situ* x-ray diffraction experiments investigated melting behavior of Al powder during shock loading[1]
  - Performed at the Dynamic Compression Sector (DCS) at Argonne National Lab
  - First direct evidence of shock-induced melting in aluminum powder
  - Time-dependent melting behavior occurring over hundreds of nanoseconds

[1]Mandal, A., et al. "Direct observations of shock-induced melting and melt kinetics in porous solids". (unpublished)

X-ray diffraction experiments at DCS

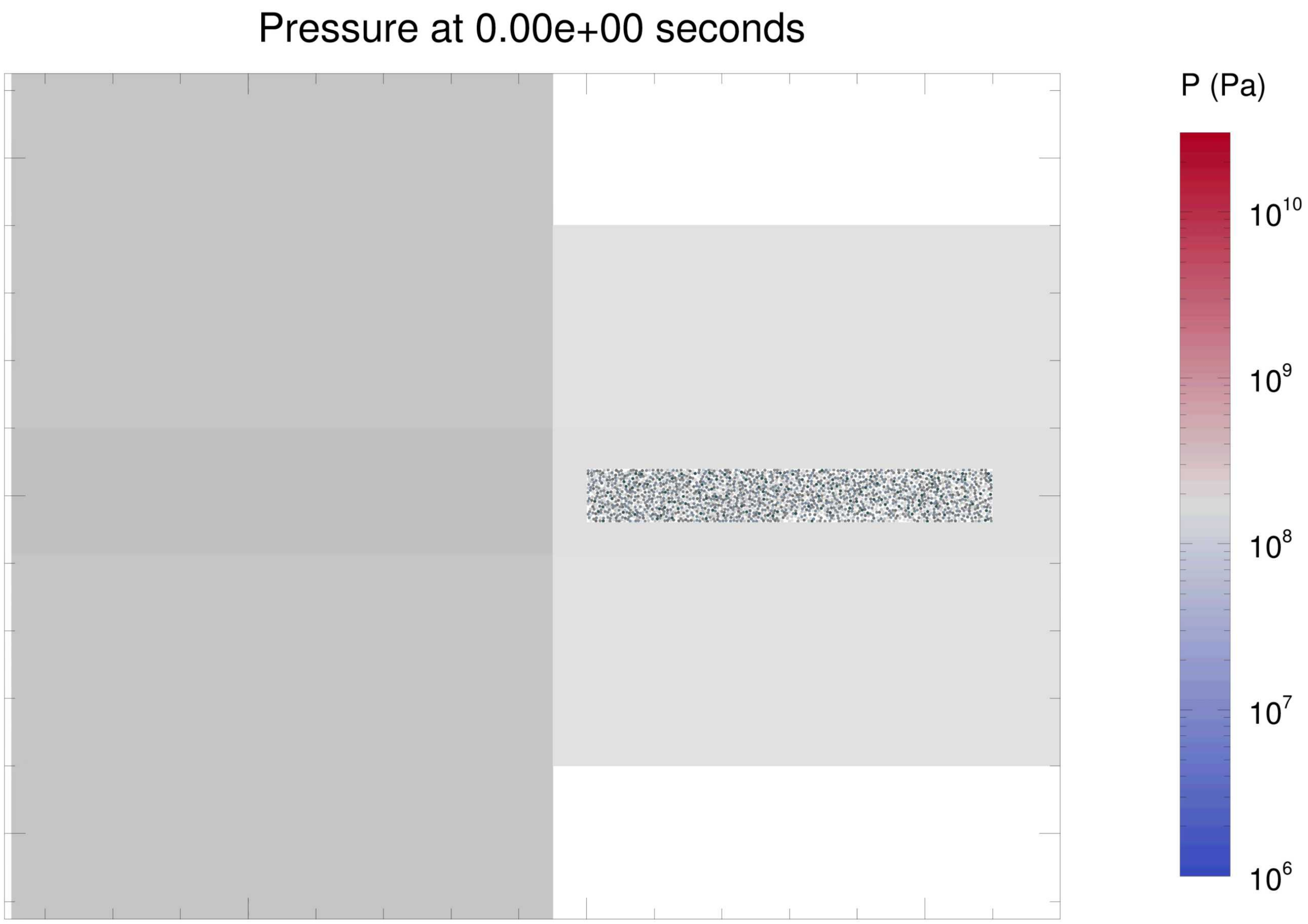


Methods to simulate shock compression of porous materials

- Traditional models for porous materials treat material as a continuum
  - Analytical models, like the P-α model[1], describe the compaction response
- Continuum simulations cannot describe heterogeneous heating occurring within shock front
  - Predict complete melting for highest velocity cases in contrast to experimental observations
- Mesoscale methods explicitly resolve individual grains in powder
  - Compaction processes within shock front simulated directly
- Goal to perform mesoscale simulations to investigate shock-induced melting behavior of Al powder over range of velocities in DCS experiments

[1]Herrmann, W. (1969). "Constitutive Equation for the Dynamic Compaction of Ductile Porous Materials." Journal of Applied Physics 40(6): 2490-2499.

Mesoscale simulation of shock generation in powder by impactor

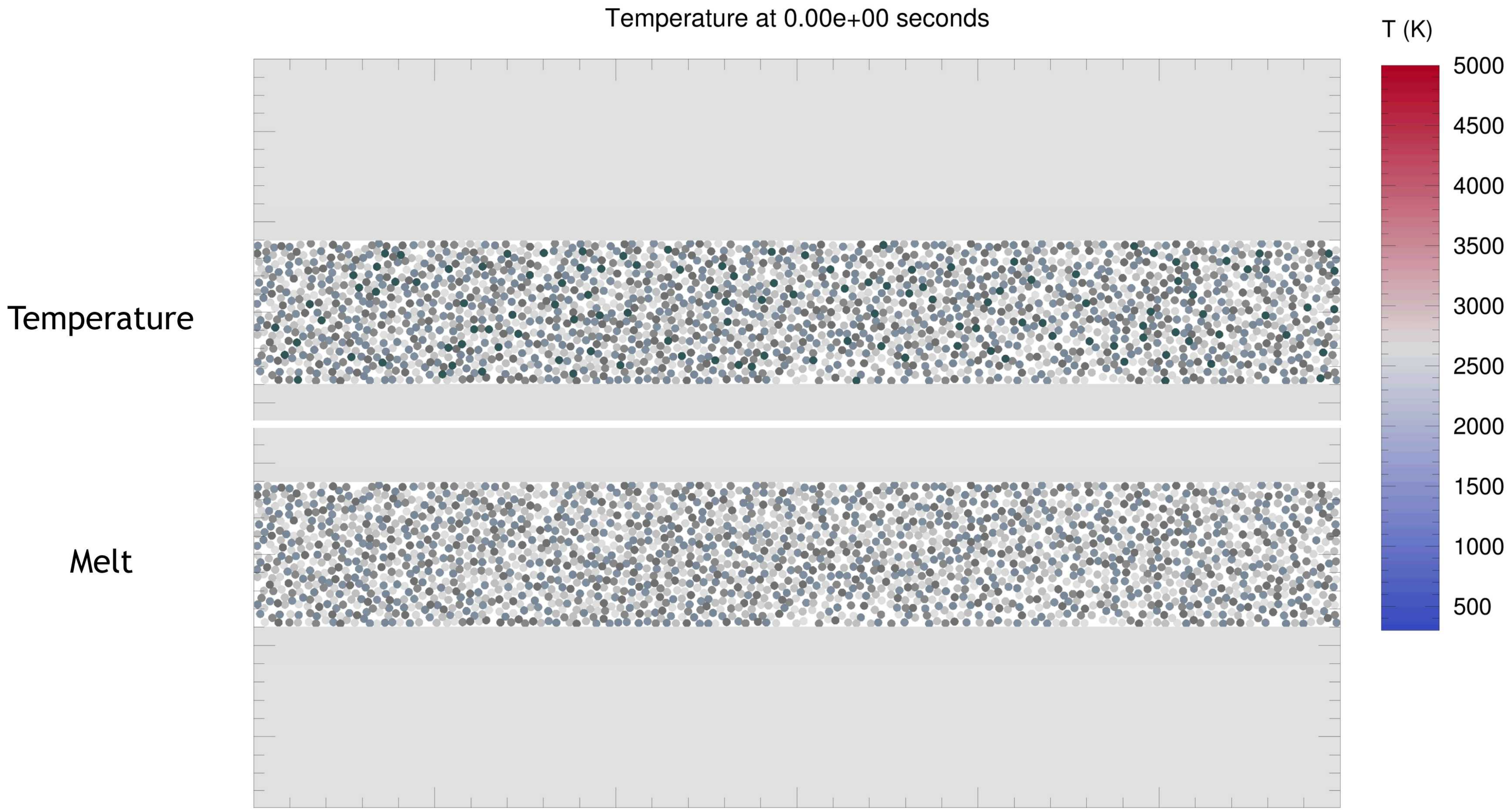


Simulation details

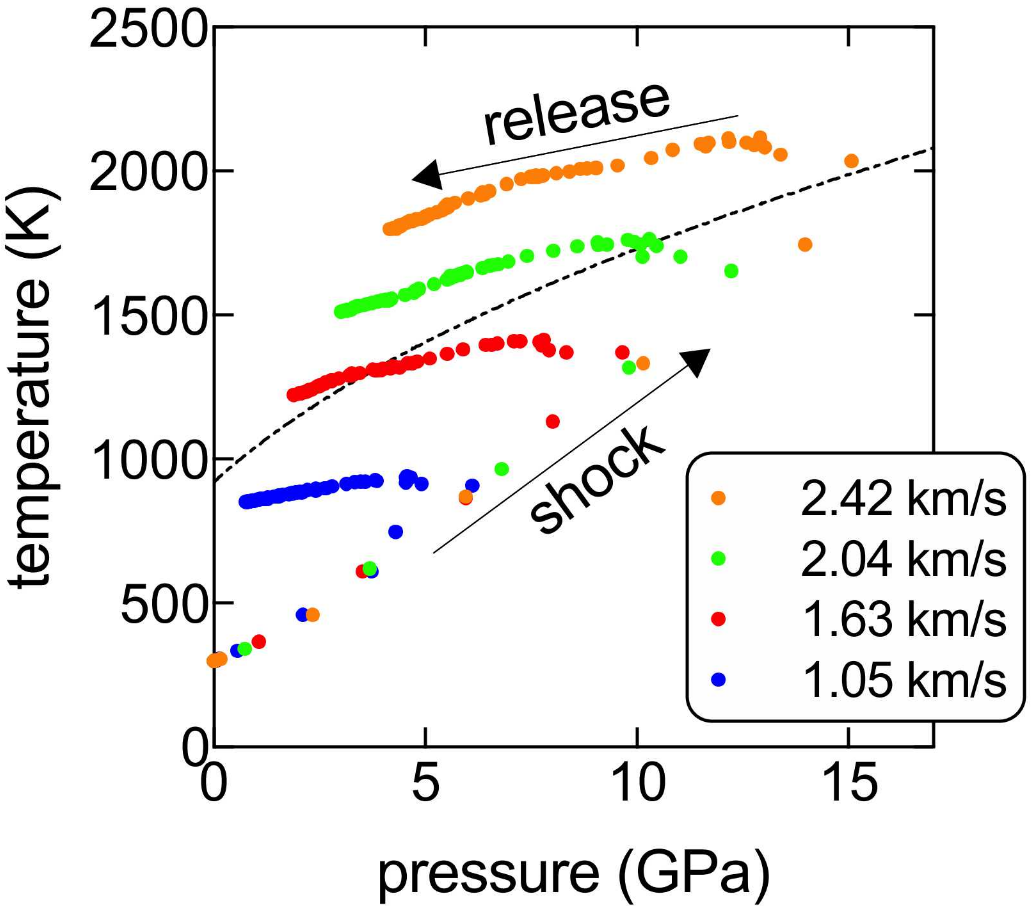
- Simulations performed using Sandia shock physics code CTH[1]
- Multi-phase equation of state[2] to describe Al grains
- Phase determined by comparing P-T state to equilibrium melt line
  - Ignores kinetics of phase transition
- Total energy conserved during remap step
  - May lead to overheating
- Explicit treatment of thermal conductivity in Al (k = 237 W/m·K)

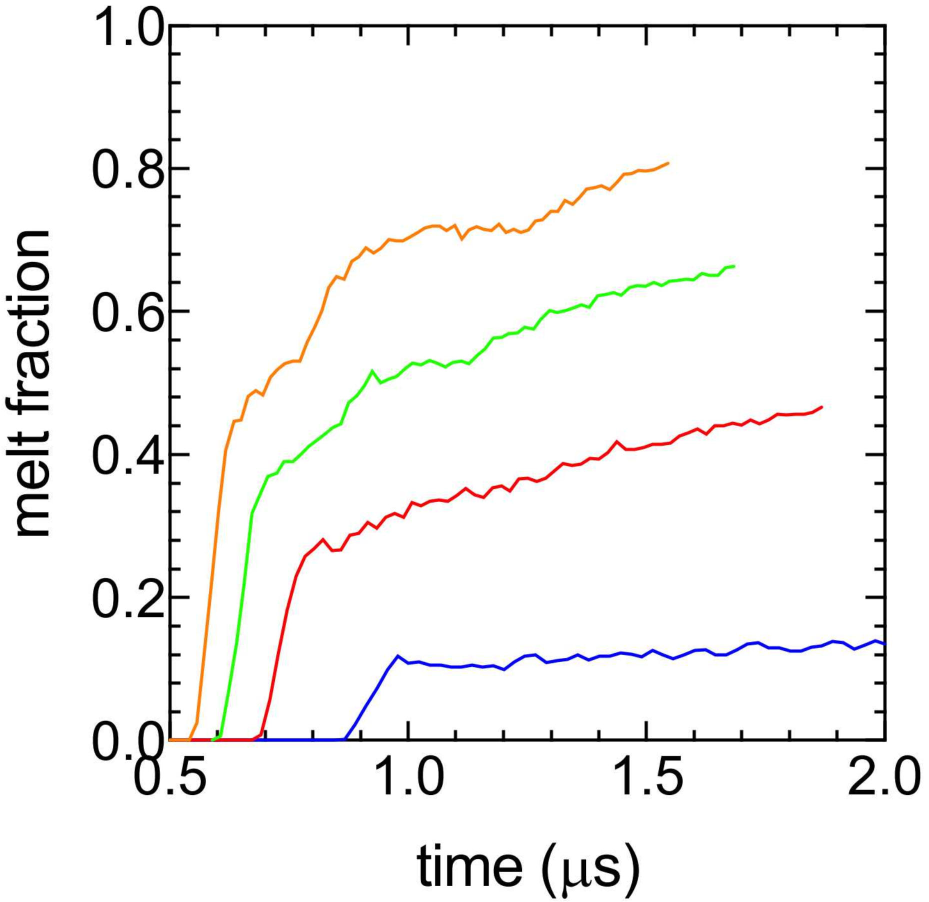
[1]McGlaun, J. M., et al. (1990). "CTH: A three-dimensional shock wave physics code." International Journal of Impact Engineering 10(1): 351-360.
[2]Kerley, G. I. (1987). "Theoretical equation of state for aluminum." International Journal of Impact Engineering 5(1): 441-449.

Heating and melting of aluminum powder at $\mathbf{v_p}$ = 2.04 km/s

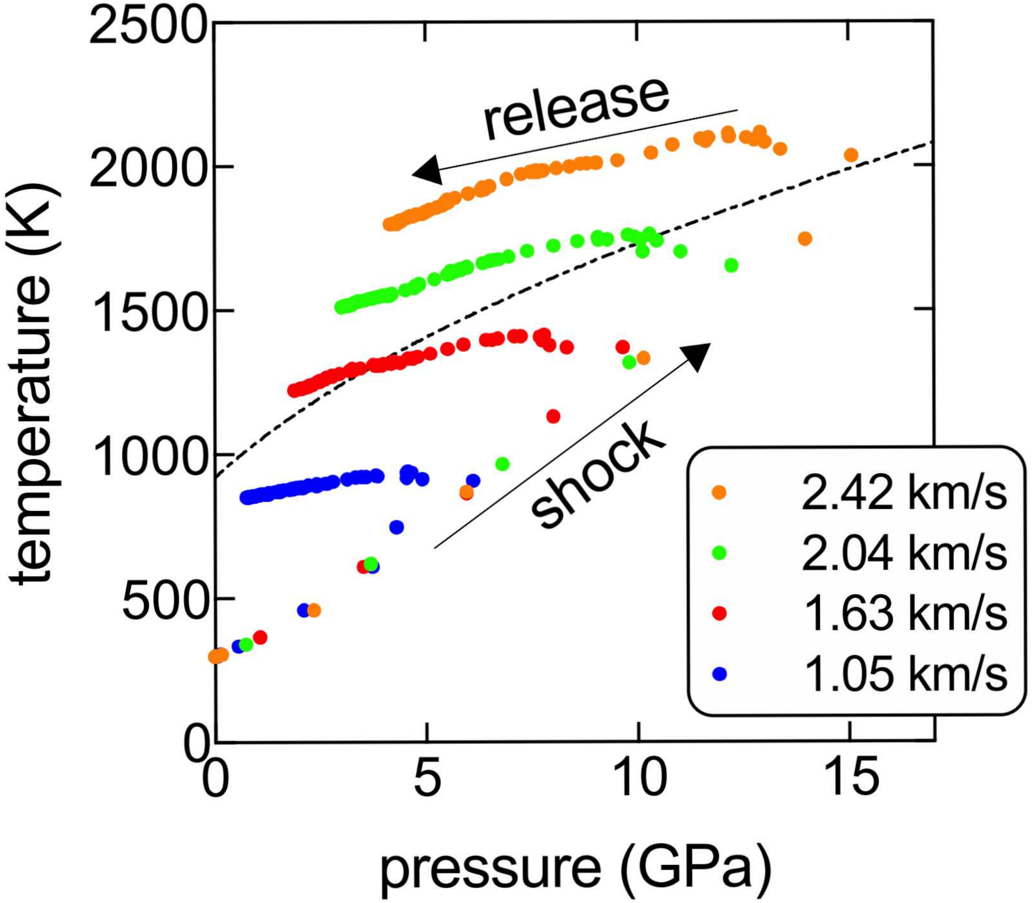


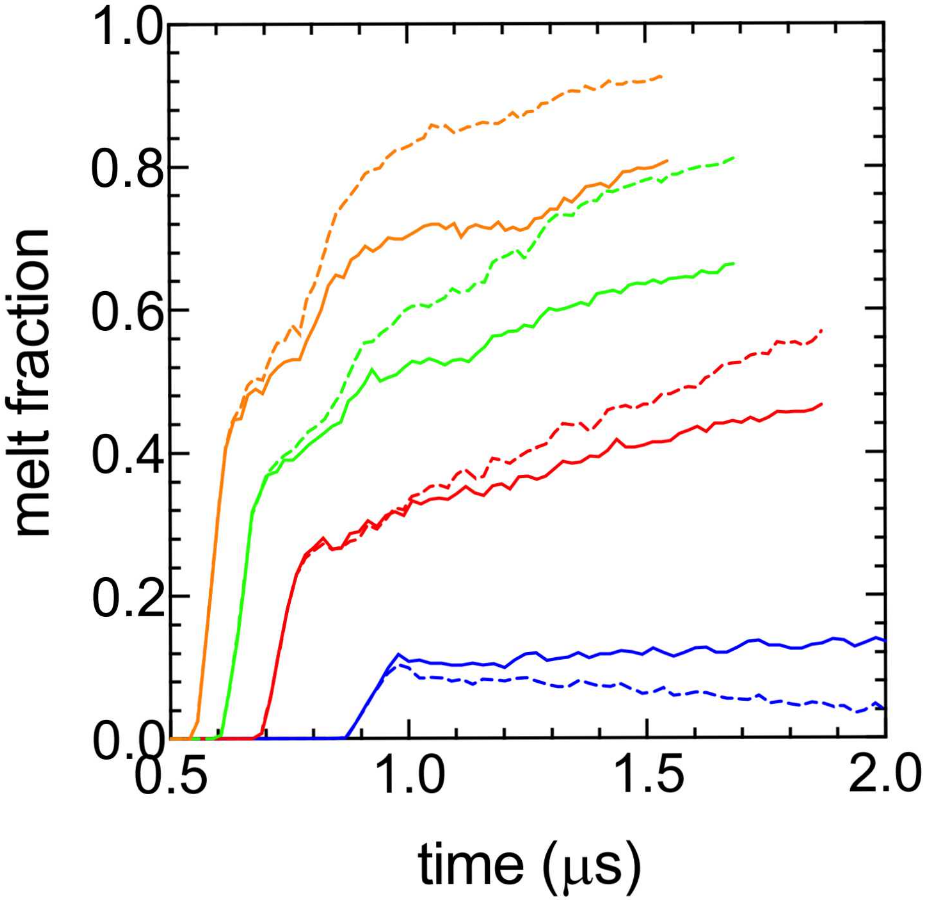
Evolution of average P-T state and melt fraction



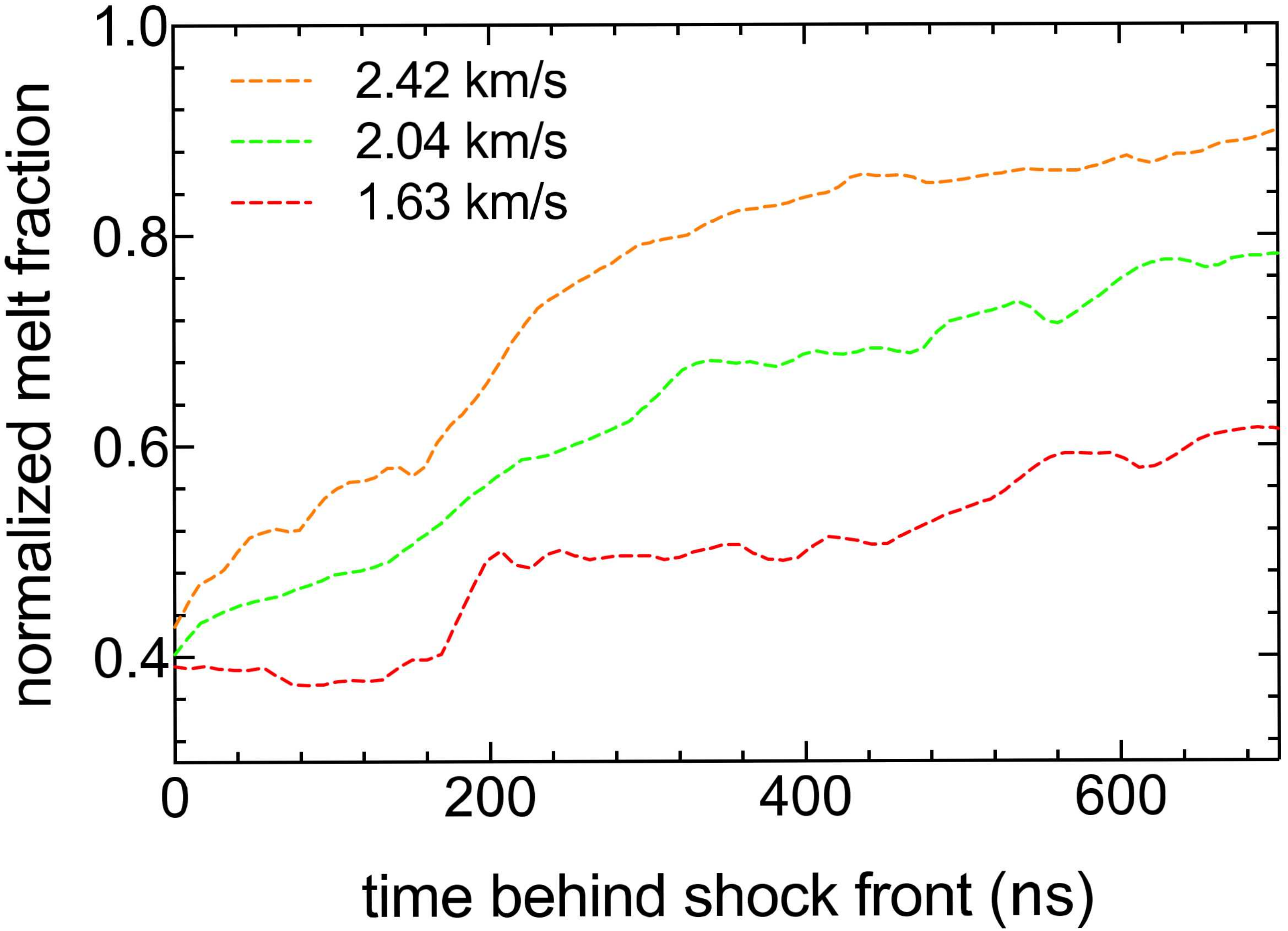


Effect of heat conduction on melt behavior

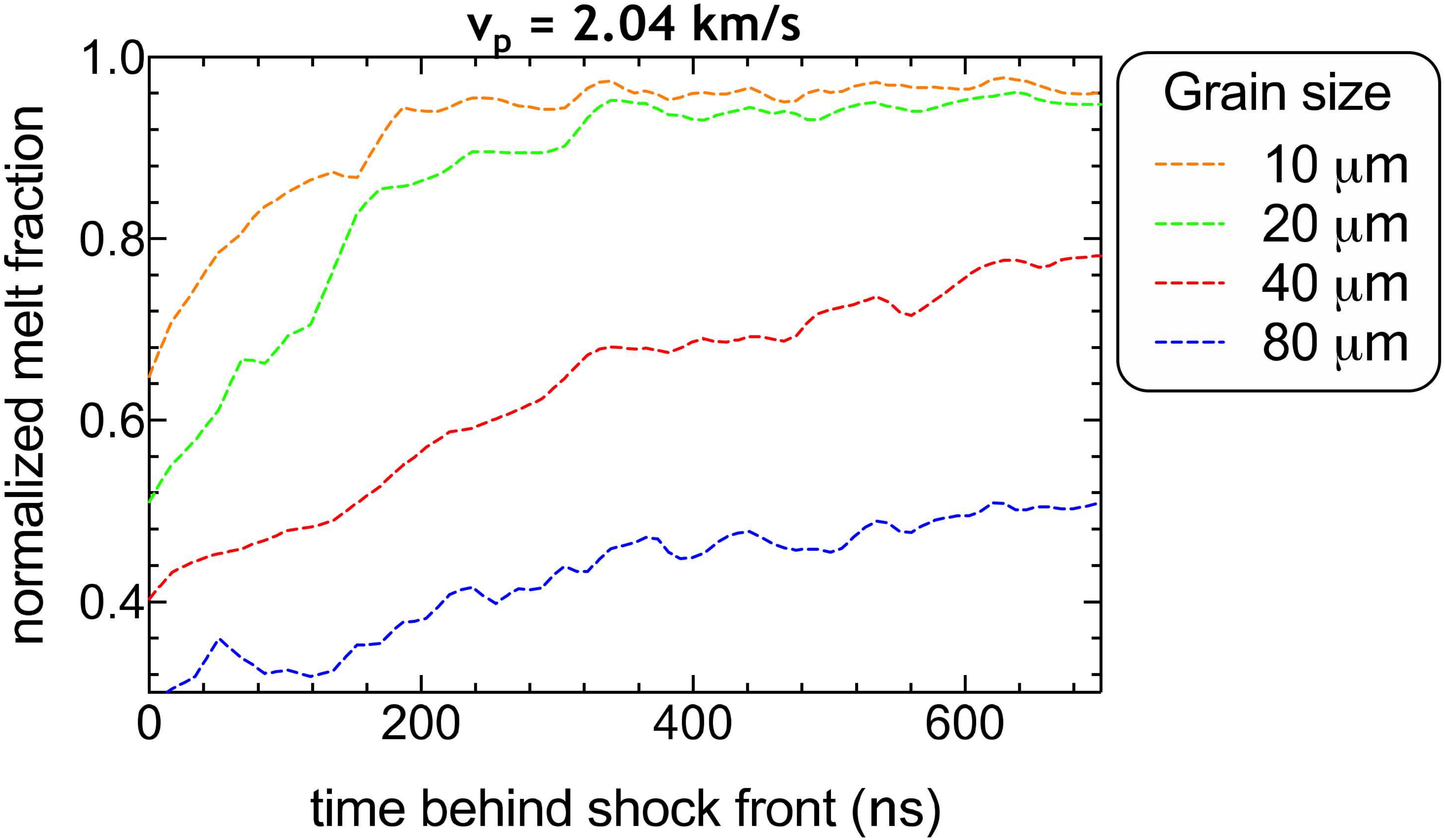




Normalized melt fraction in shocked state



Grain size effect on time to reach thermal equilibrium



Summary of powder melt results

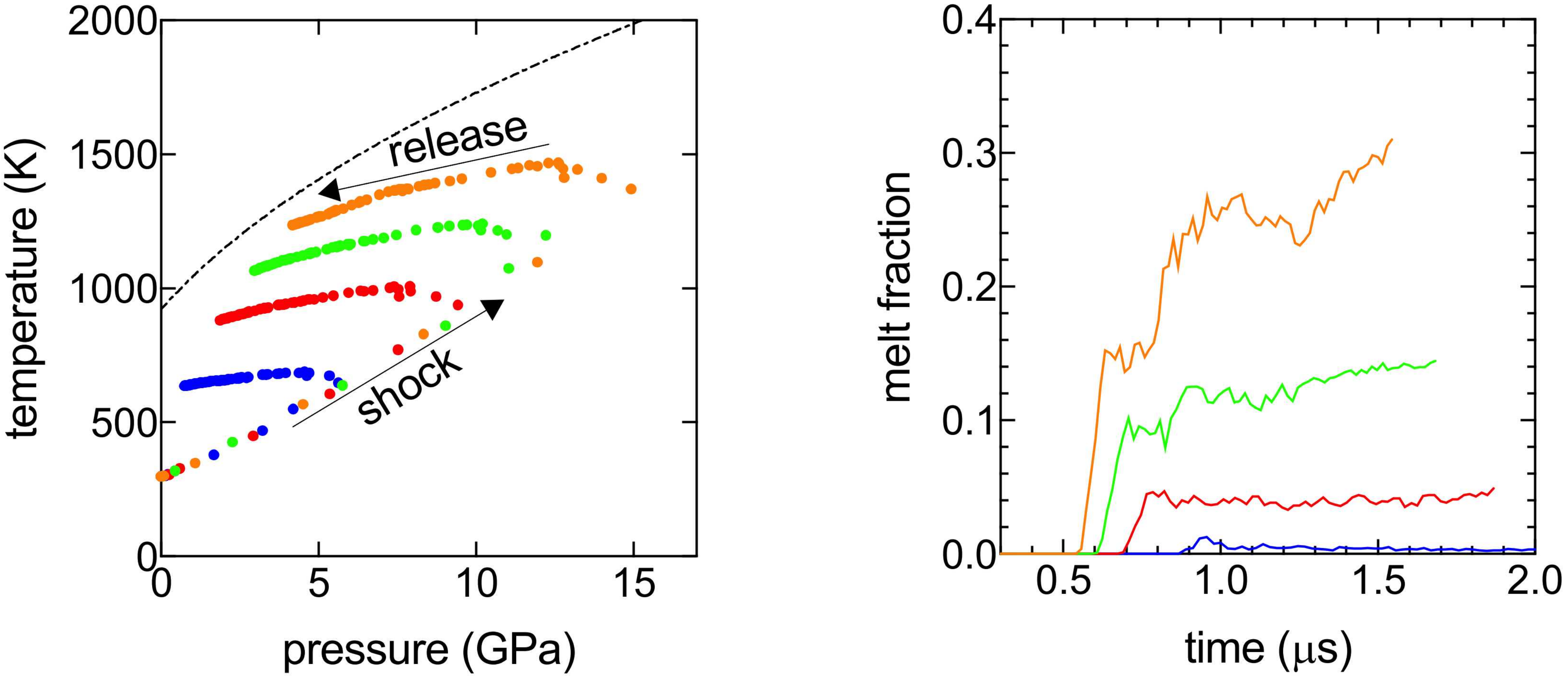
- Mesoscale simulations show shock heating of powder is very heterogeneous
  - Leads to time-dependent melting behavior as observed in DCS experiments
- Thermal conduction within the powder leads to
  - Less melting at low impact velocities as hot regions cool below melt temperature
  - More melting at high impact velocities as cooler regions are heated above melt temperature
- Thermal equilibrium not achieved within duration of mesoscale simulations ($\geq$ 650 ns)
- Smaller particles melt faster than larger ones
  - Mesoscale simulations predict complete melt for 20 and 10 μm grains within 400 ns at 2.04 km/s

Acknowledgments

- DCS experiments performed by
  - Matt Hudspeth (LANL)
  - Anirban Mandal (LANL)
  - Brian Jensen (LANL)
  - Ryan Crum (LLNL)
- Also, thanks to Tracy Vogler for help with CTH and mesoscale simulations

Additional slides

Evolution of average P-T state and melt fraction (internal energy advection)



Grain size effect on time to reach thermal equilibrium