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Hugoniot and melt properties of Beryllium and Diamond for ICF capsule physics

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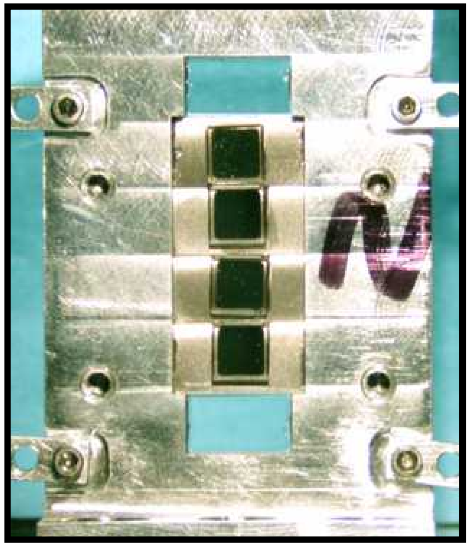

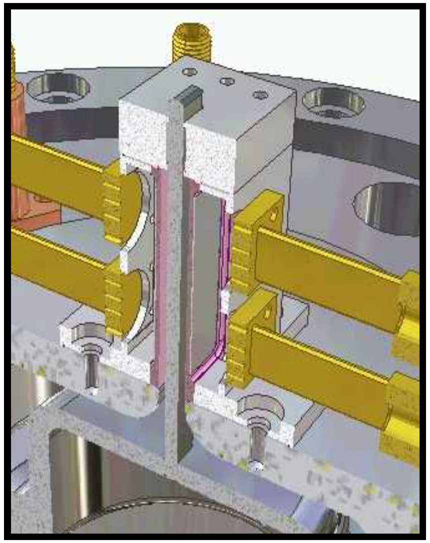

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• Ray Lemke	MHD simulations
• Jim Asay	Strength discussions
• LLNL NIC IET	Be experimental configuration
• LANL NIC IET	Be experimental configuration
• Z Operations crew	

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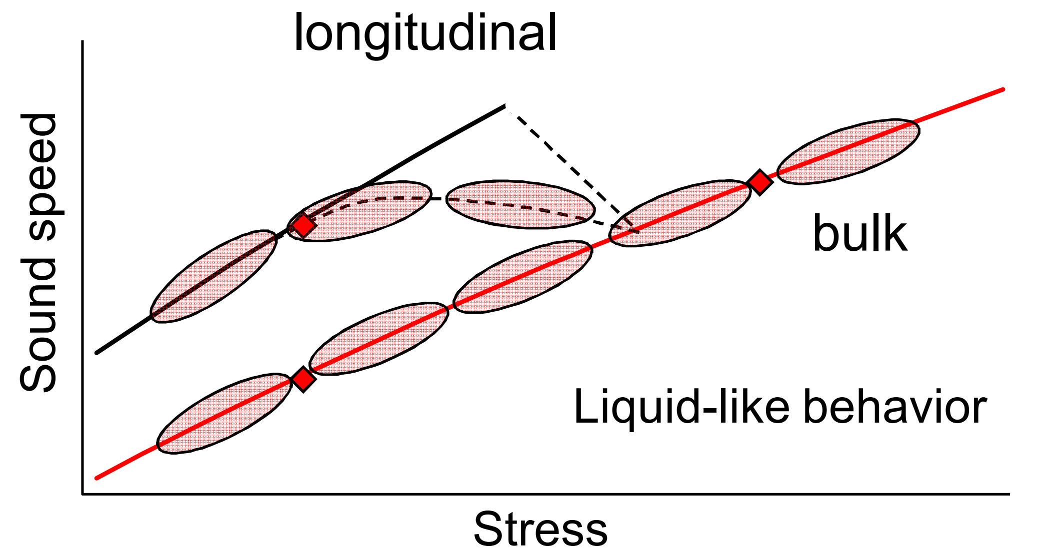
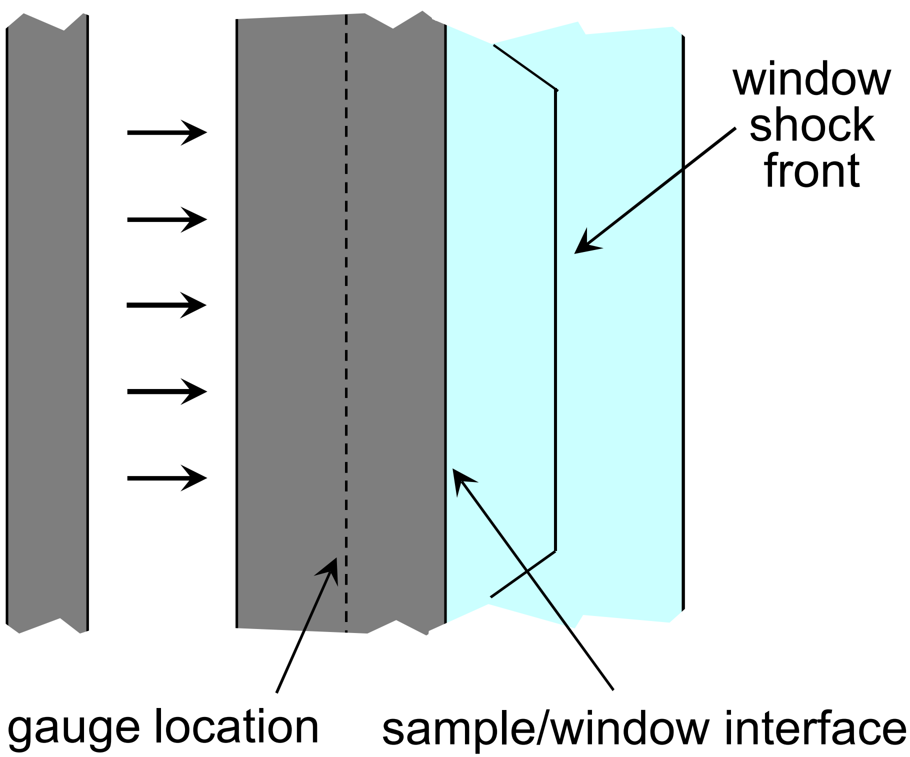
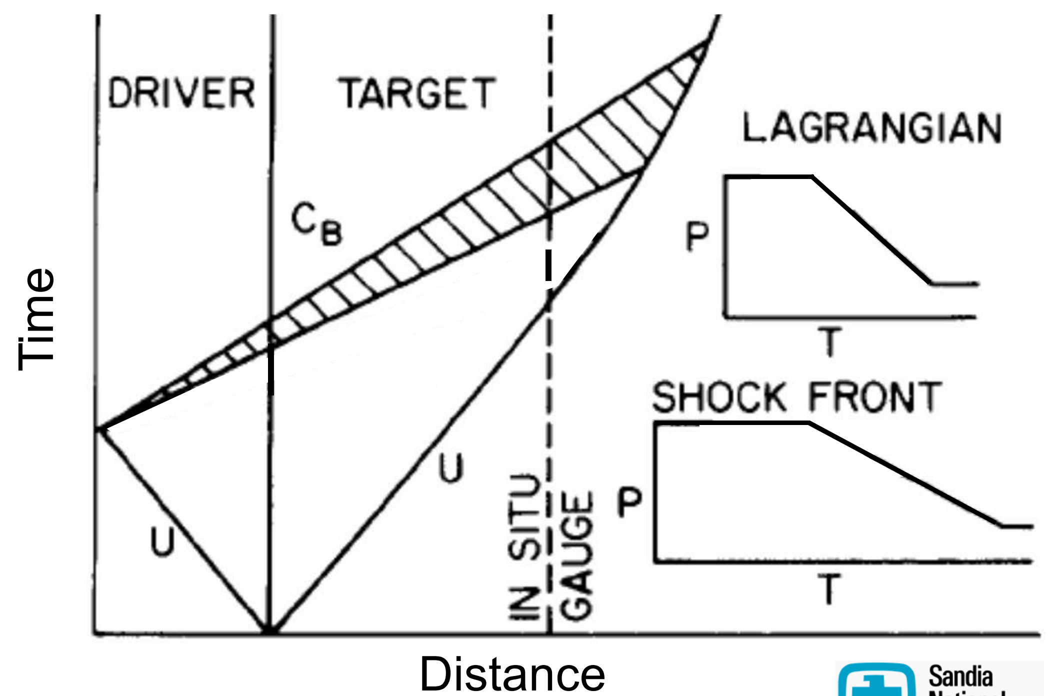
Sound speed measurements were performed to identify the onset of melt

- Well accepted method to identify melt on the Hugoniot
- Requires multiple experiments over a broad stress range
- Can also provide information regarding the yield strength on the Hugoniot







McQueen, et al., Rev. Sci. Instrum. **53**, 245 (1982)

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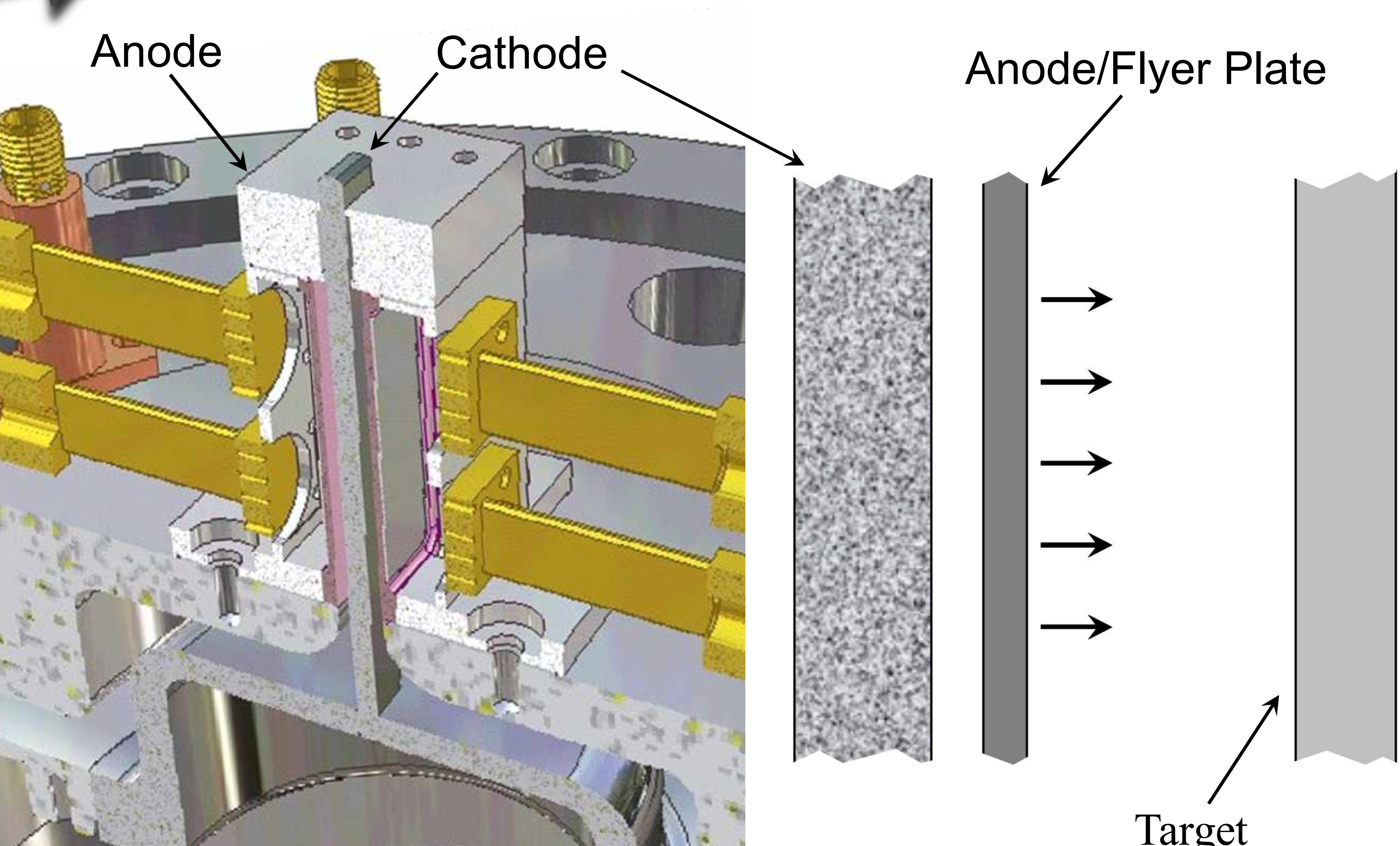
These experiments utilize the ultra-high velocity flyer plate capability on Z



M.D. Knudson, et al., J. Impact Eng., **29**, 377 (2003)

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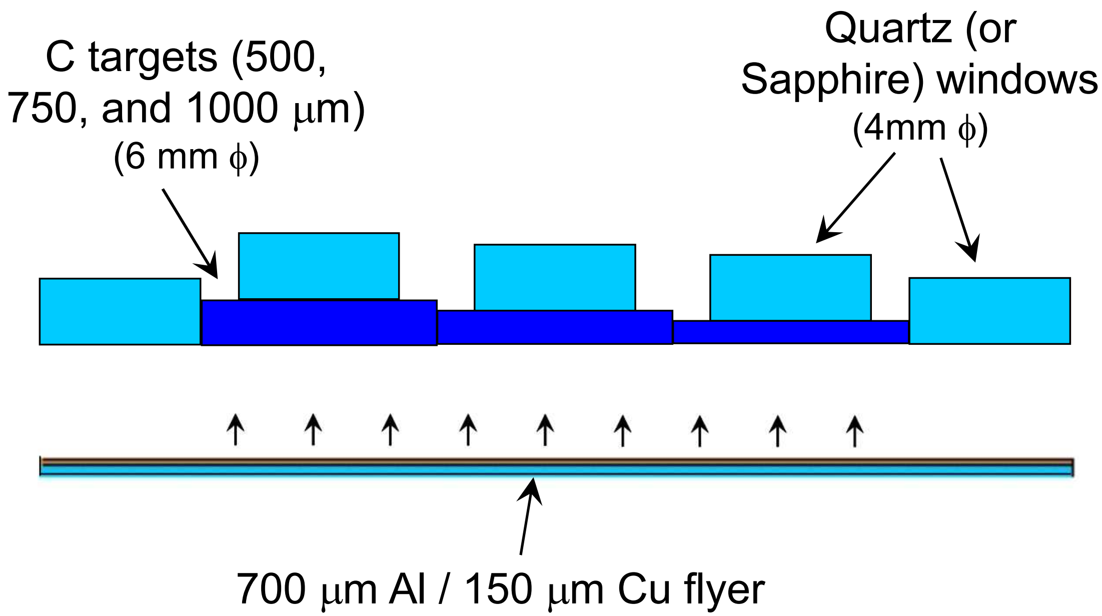
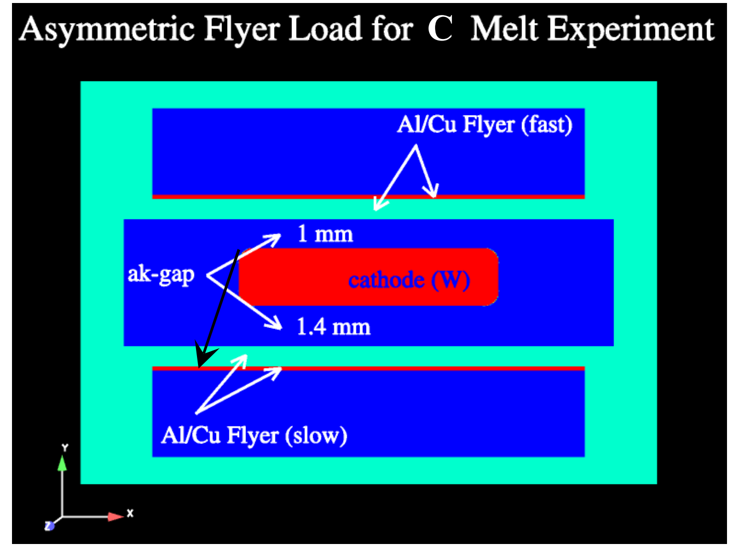
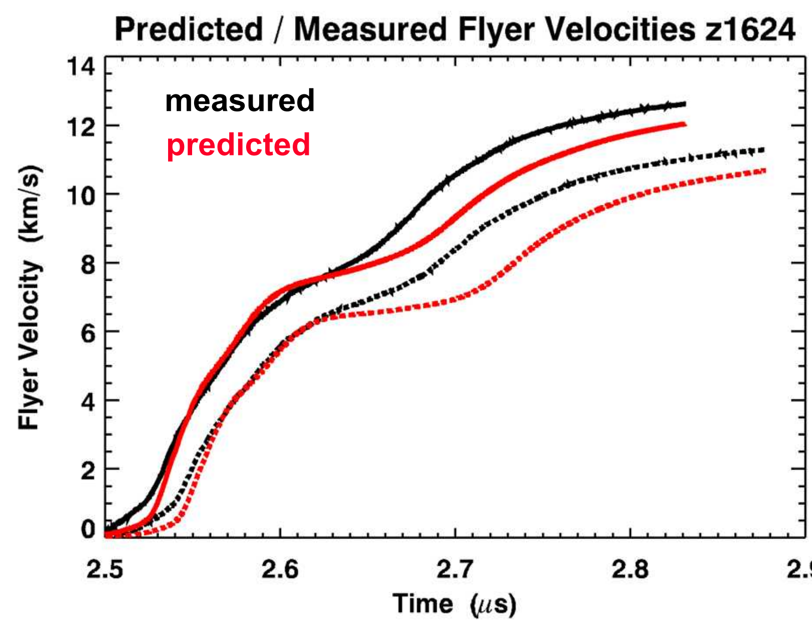
MHD simulations were critical in providing load geometries to achieve desired flyer velocities







- Experiments required an Al/Cu flyer with peak velocities in the range of 7-24 km/s
- Three asymmetric loads were designed to produce 2 flyers per shot with ~10% difference in peak velocity
- ALEGRA 2D MHD was used to set flight distances and to set charge voltages on Z

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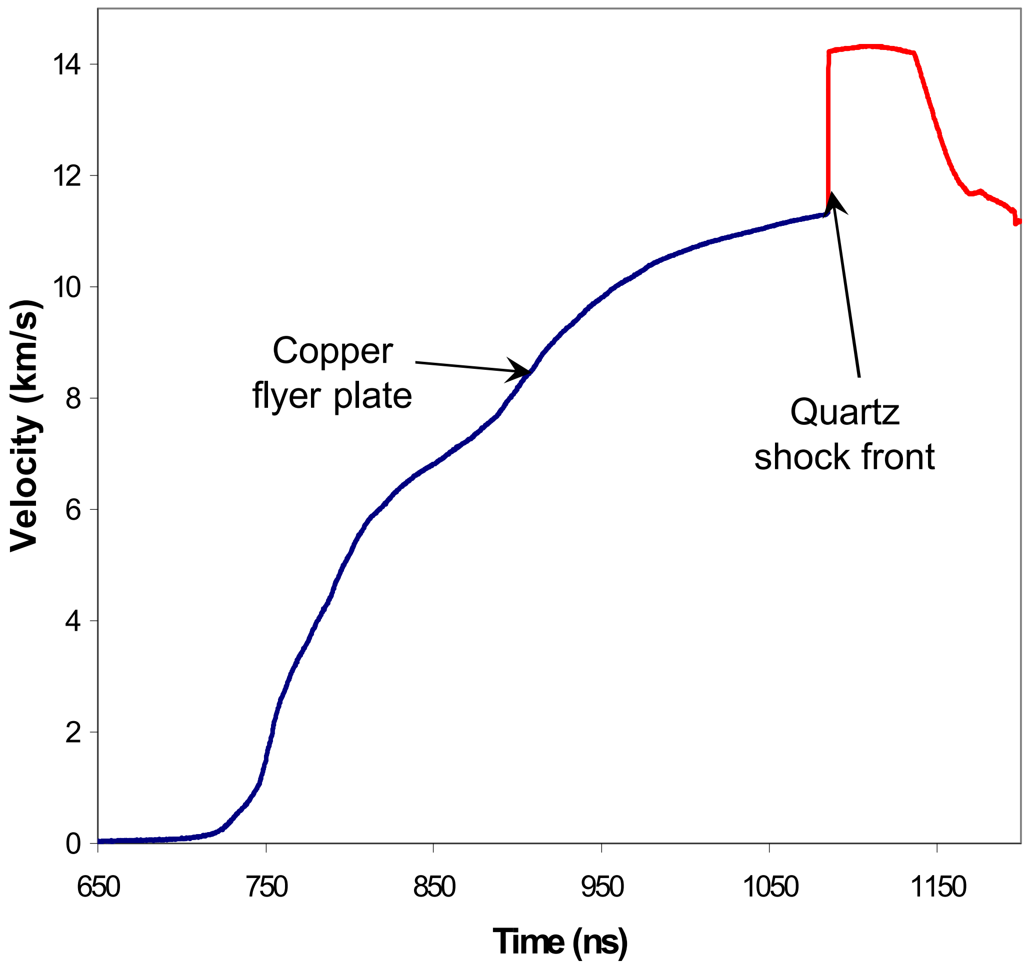
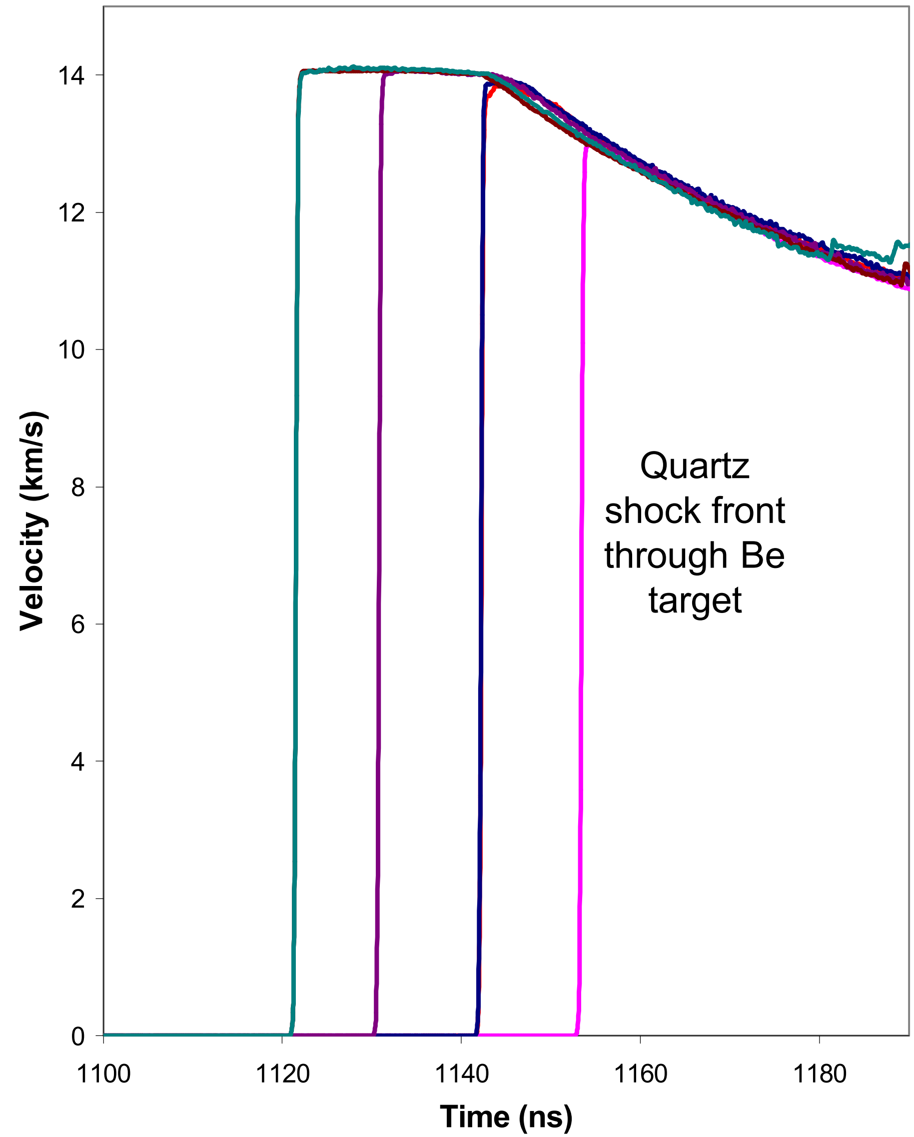
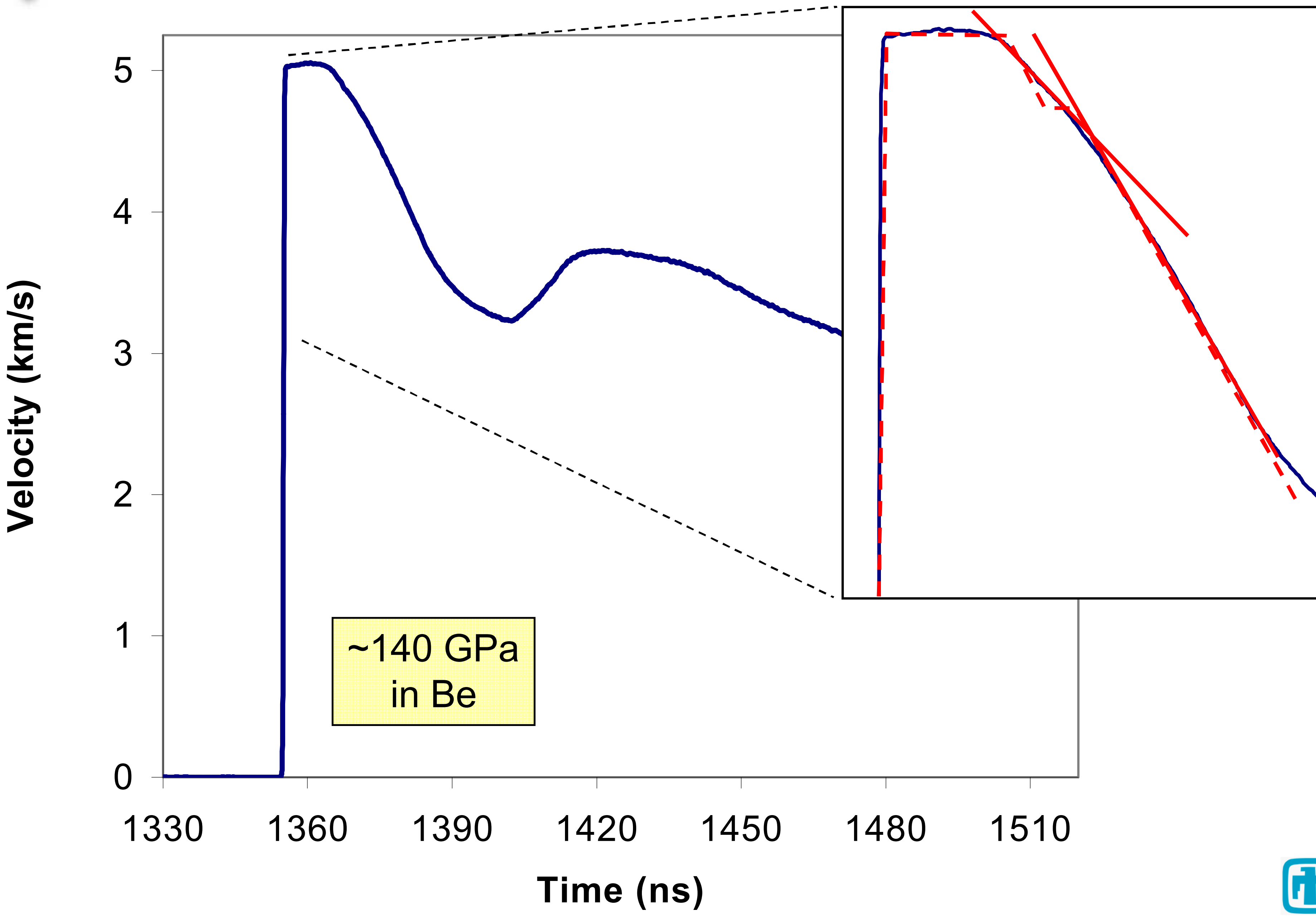
High quality data was obtained from the Be melt experiments

Sample data at ~2.5 Mbar in Be

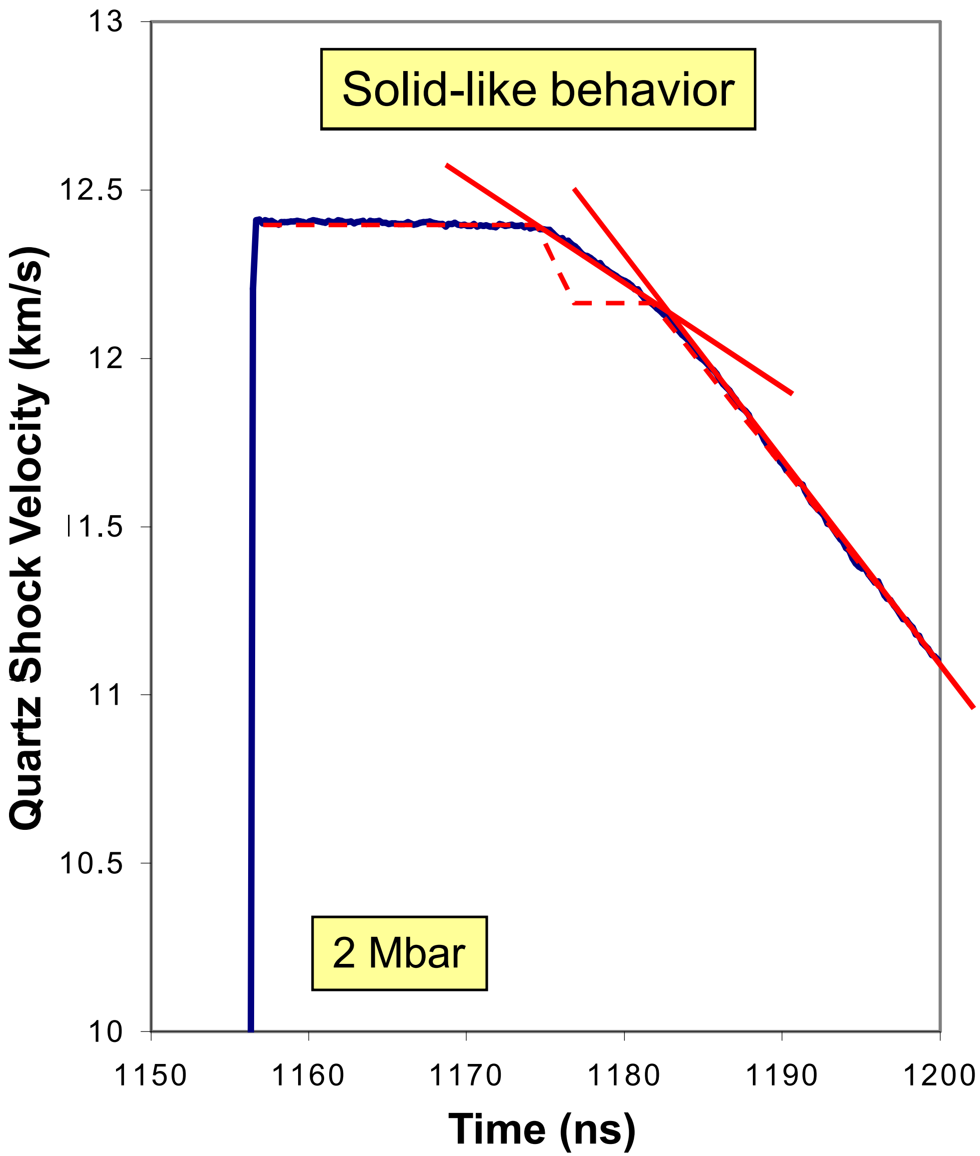


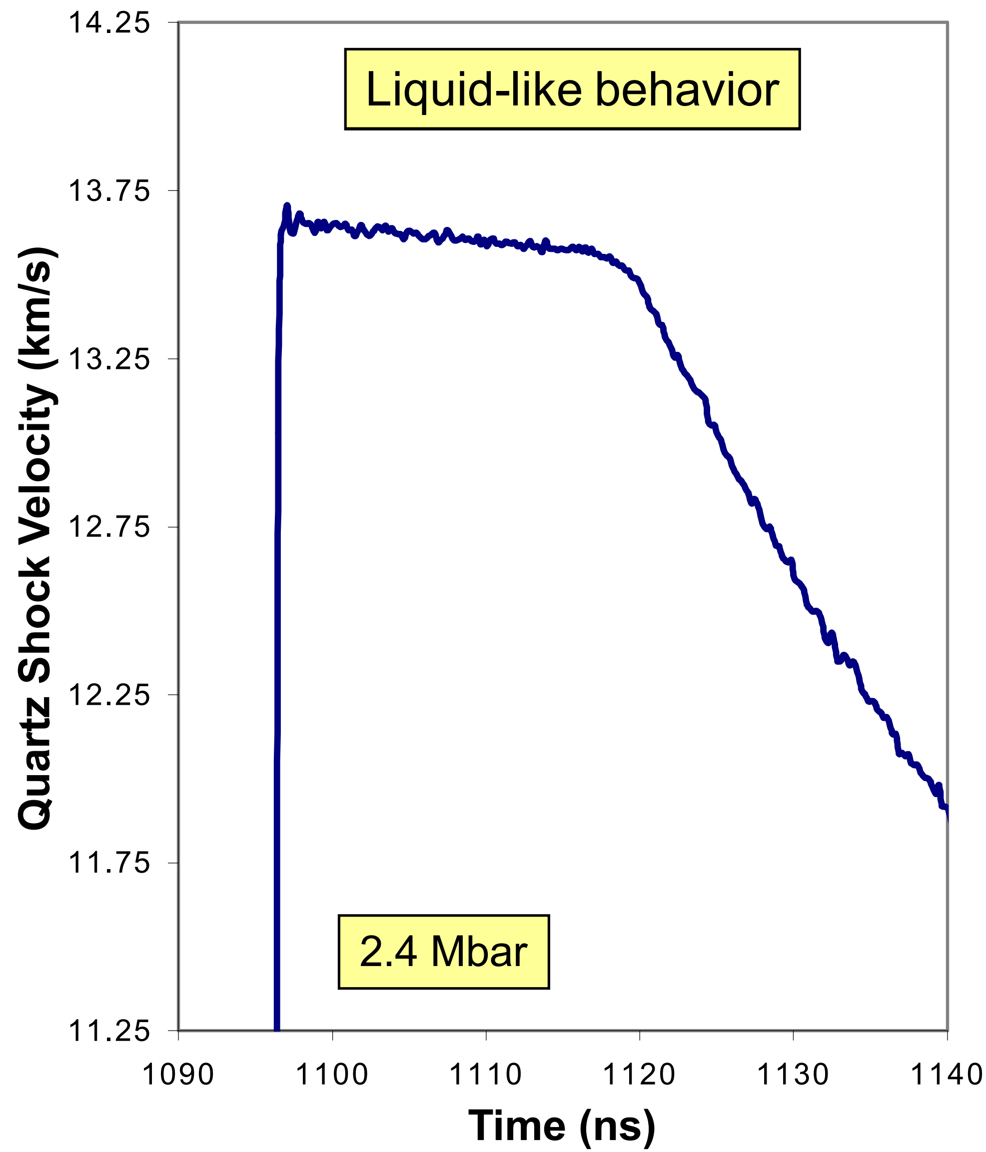


Classic elastic/plastic release observed at lower stresses with LiF window



Experiments clearly show solid-like behavior at low stresses and a loss of strength at higher stresses





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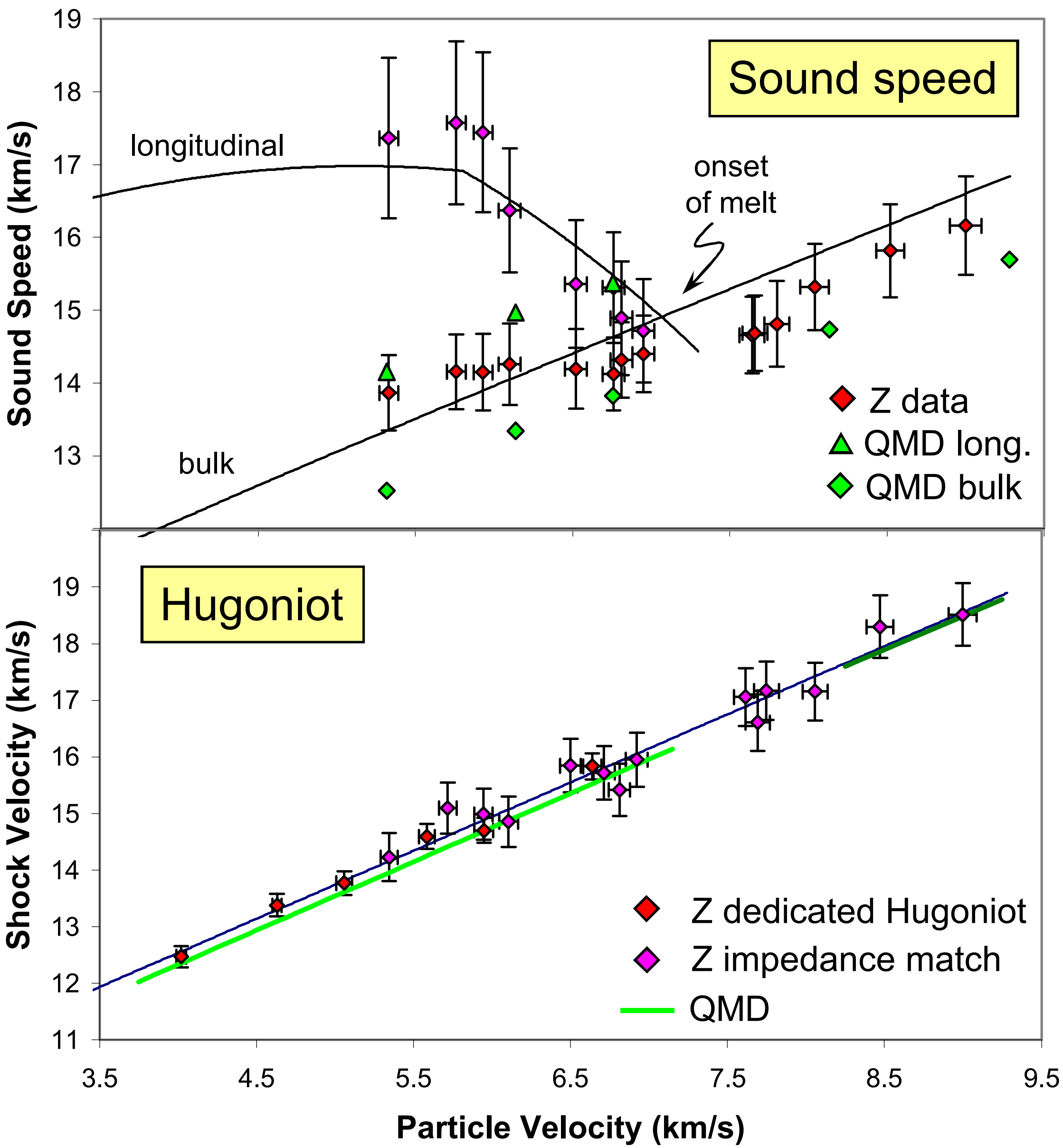
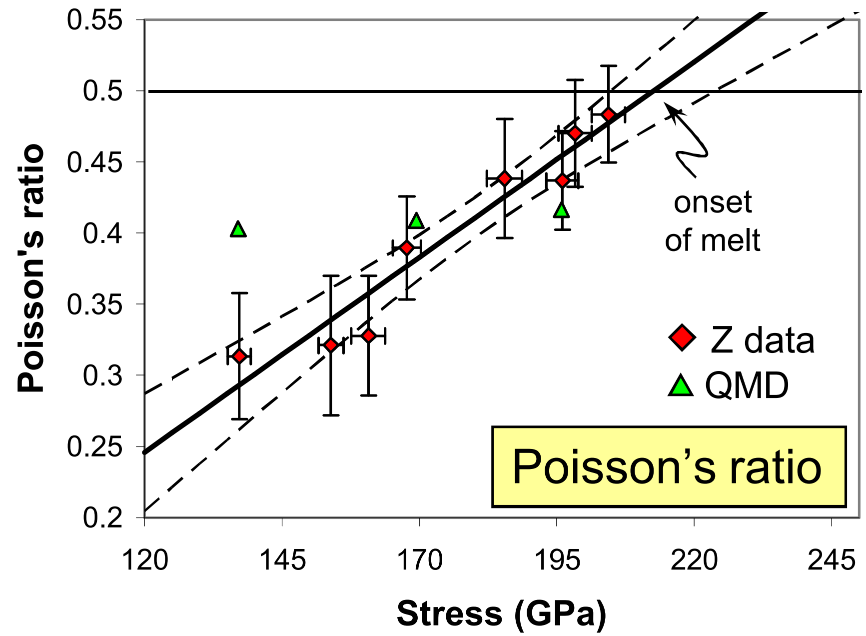
Comparison of Hugoniot and sound speed measurements with QMD calculations for bcc Be





- QMD bcc Hugoniot appears systematically soft relative to experiment
- QMD bulk sound speed in decent agreement with experiment
- QMD longitudinal sound speed significantly low relative to experiment

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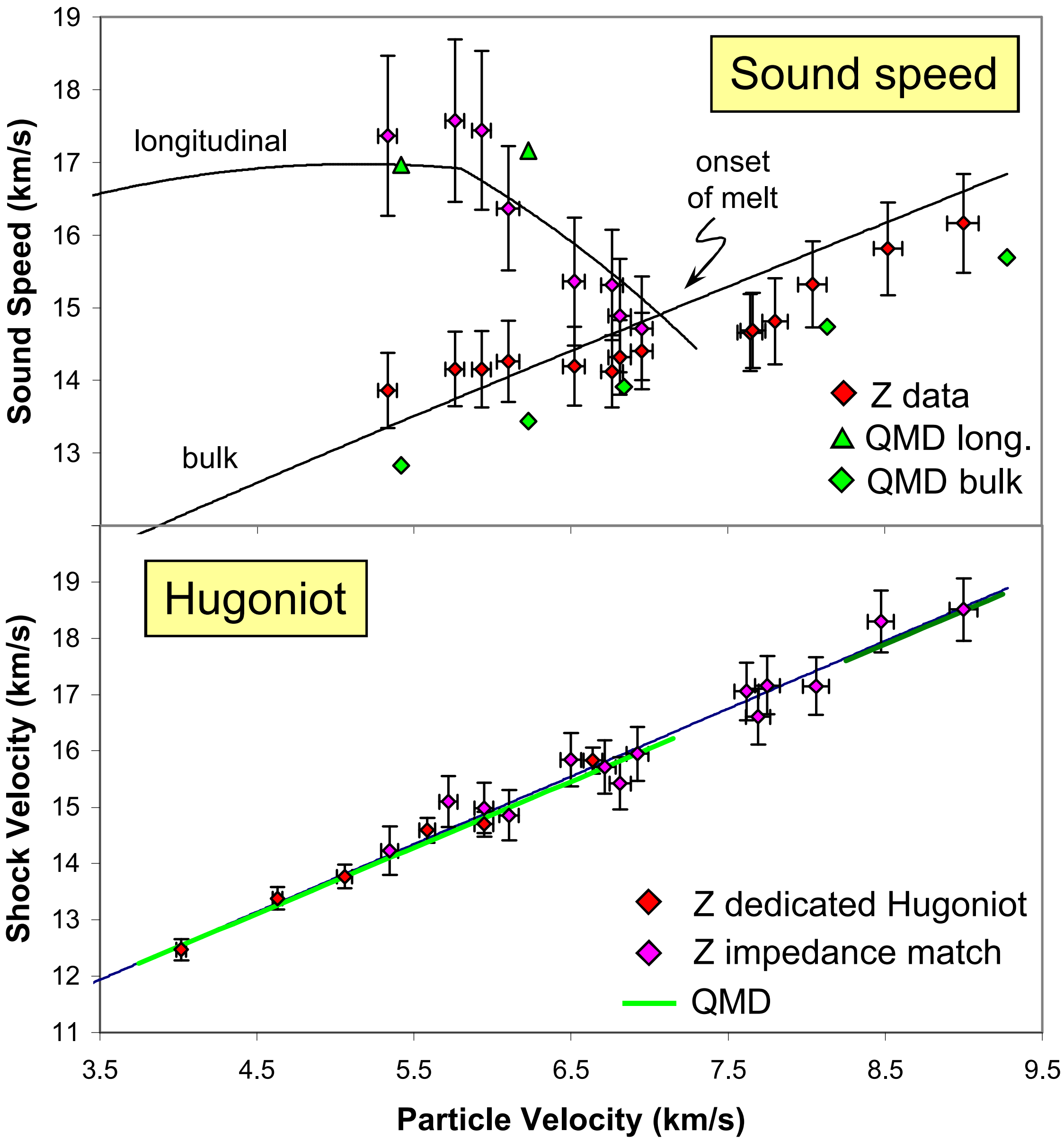
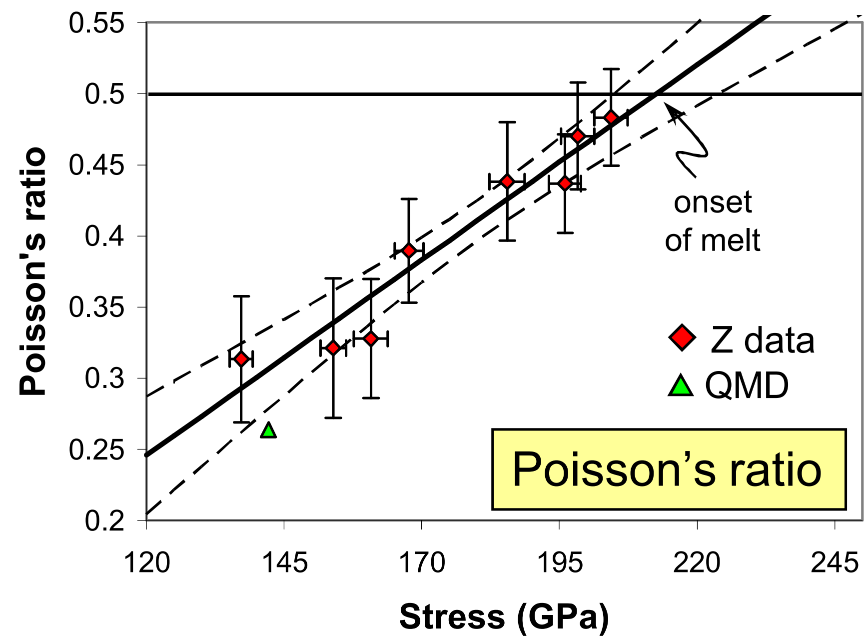
Comparison of Hugoniot and sound speed measurements with QMD calculations for hcp Be





- QMD hcp Hugoniot in better agreement with experiment
- QMD bulk sound speed in decent agreement with experiment
- QMD longitudinal sound speed in much better agreement with experiment

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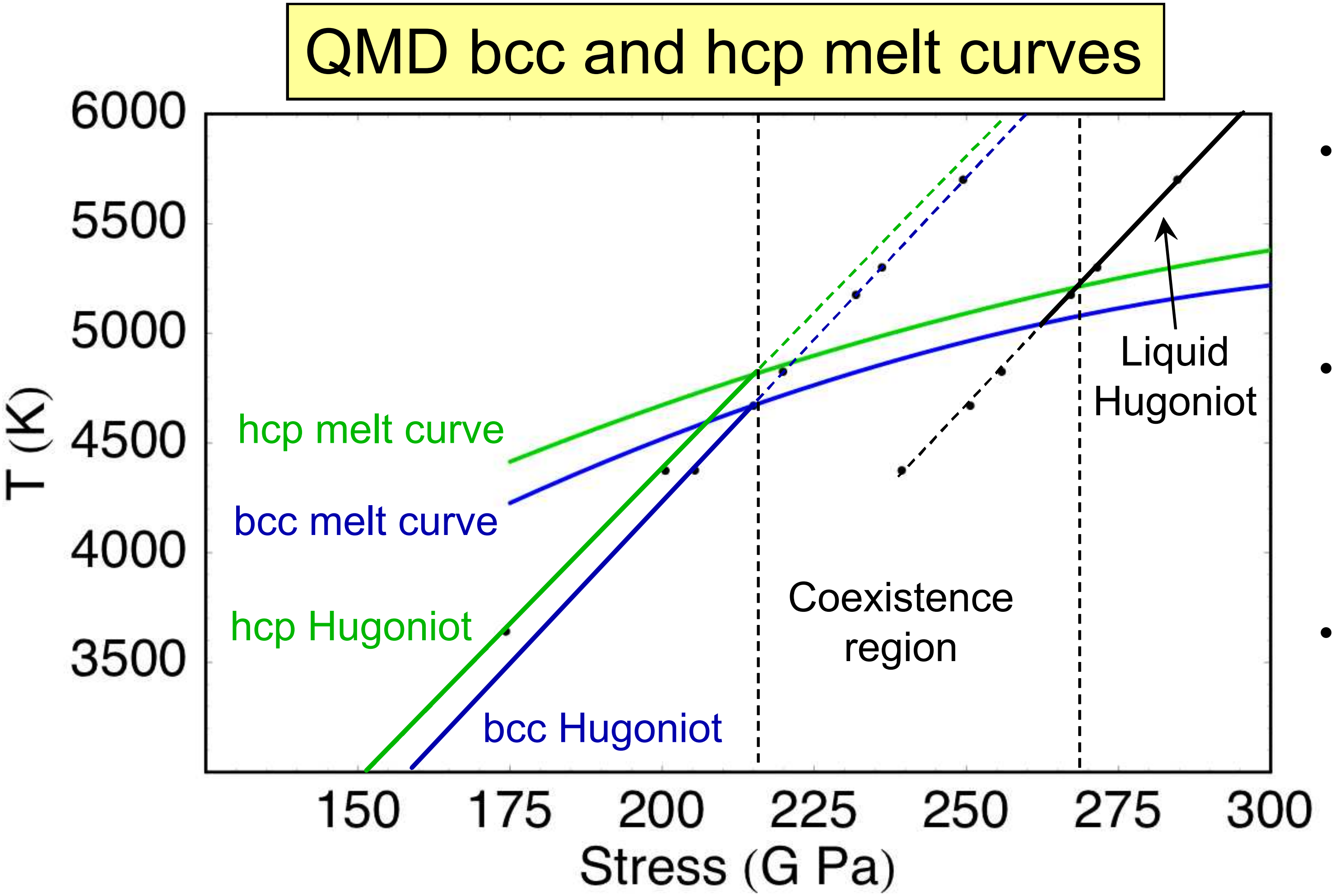
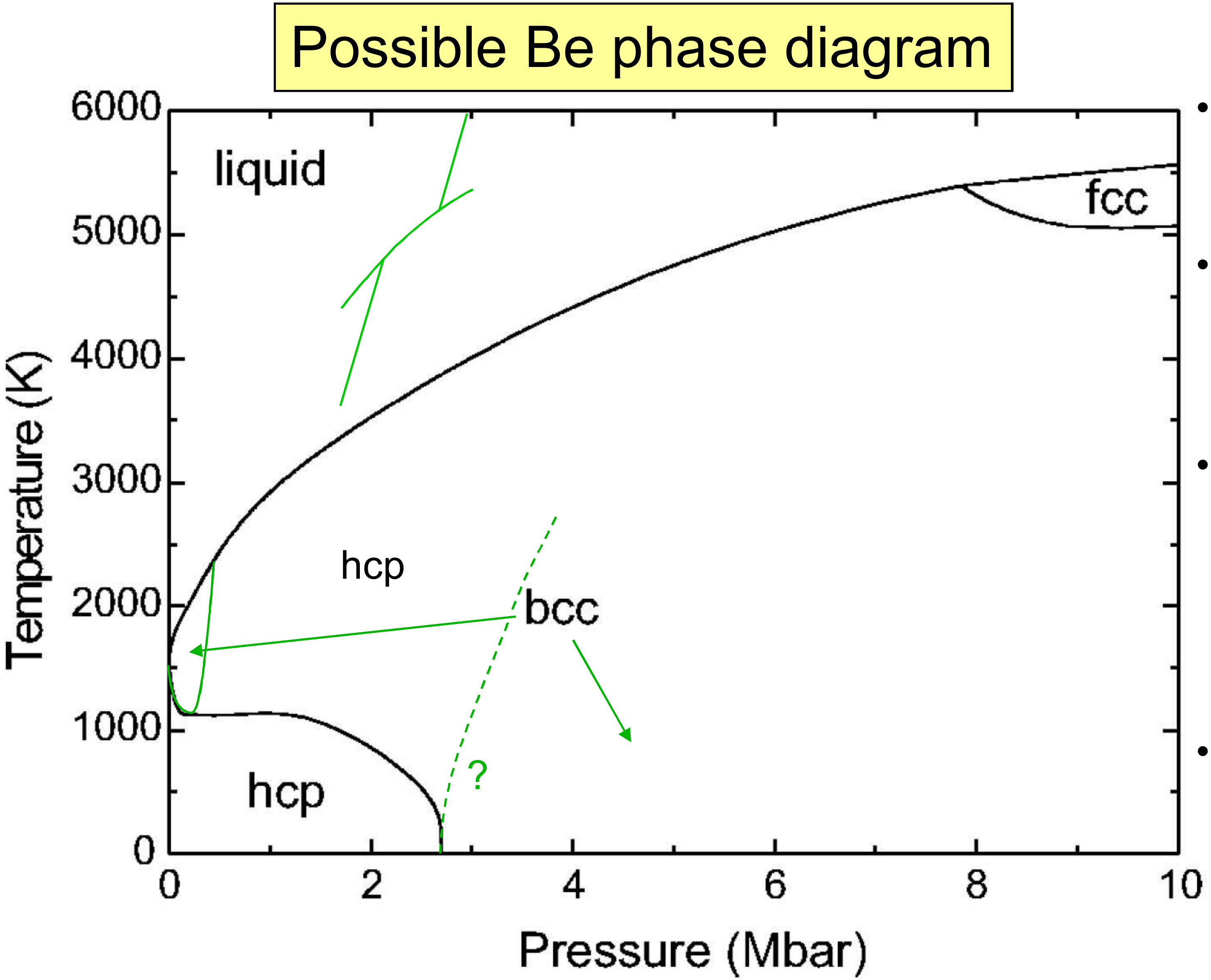
Melting from hcp rather than bcc has a negligible effect on the predicted melt region



- Relatively small temperature difference between bcc and hcp melt curves
- Predicted onset of melt nearly identical for the two phases due to offset in Hugoniot temperatures
- Both results are in very good agreement with the experimental determination of melt

Calculations predict the hcp phase to be favored over bcc in this entire region – indicates that the hcp to bcc transition is at higher stresses (~300+ GPa)

Experimental and theoretical results have led us to revisit the Be phase diagram



- Now considering two separate regions of bcc in the phase diagram
- Low pressure region could have a minimum in the hcp-bcc boundary
- Necessary but not sufficient condition would be a line of $\Delta v=0$, which has been confirmed via QMD calculations
- This scenario would provide a path for the Hugoniot to remain in hcp to melt

Sin'ko and Smirnov, Phys. Rev. B **71**, 214108 (2005)

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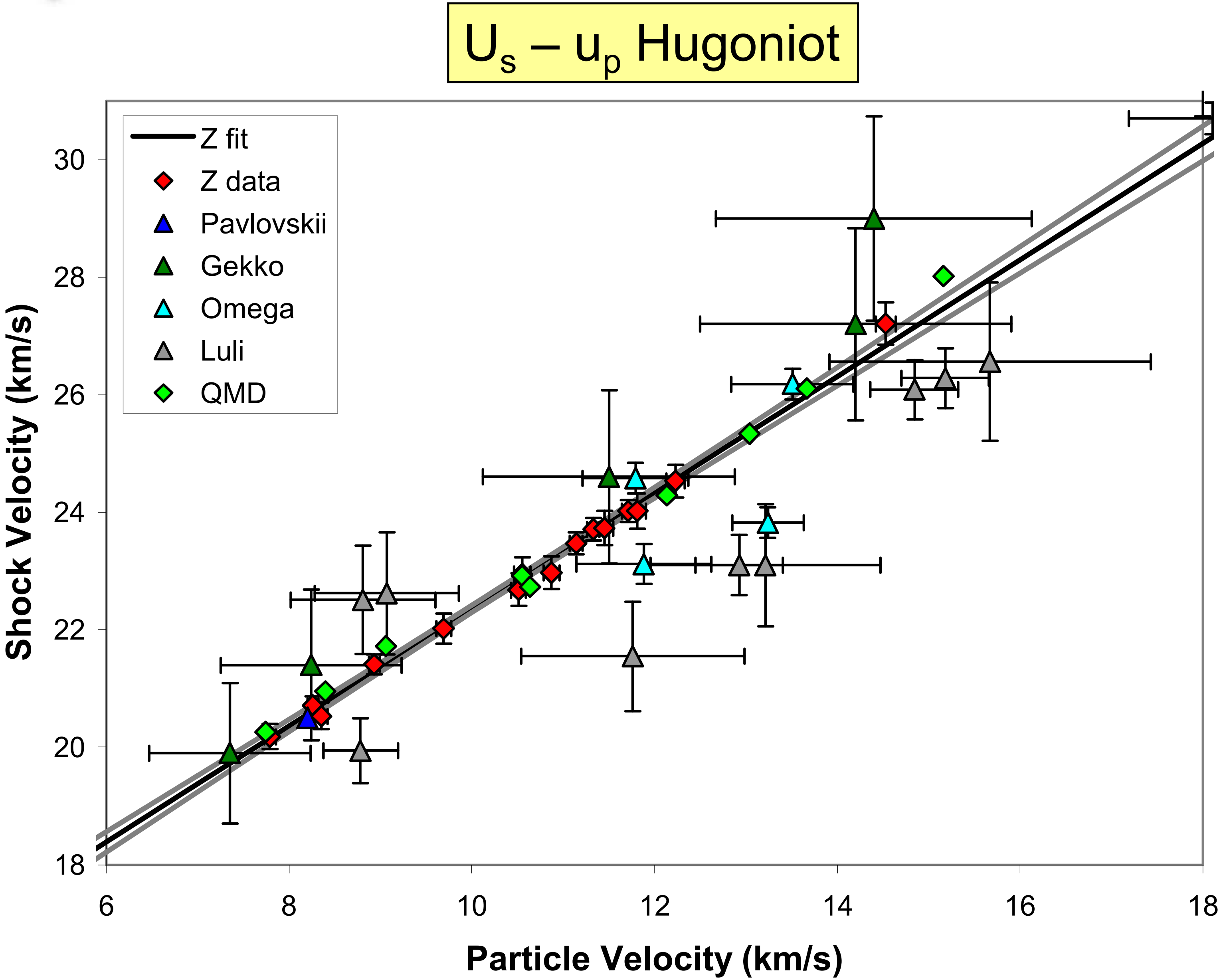
Be Conclusions

- All data obtained for Be is consistent with melt at ~210 GPa from the hcp phase
  - Does not melt from bcc as previously expected
- QMD calculations predict completion of melt at ~260 GPa
  - Appears to be in agreement with experimental data, although the indication of complete melt in the data is subtle
- Steinberg-Guinan model for yield strength in Be is in reasonable agreement with yield strength inferred from release profiles
  - Approximately 10 fold increase in yield strength over ambient
  - Yield strength collapses ~50 GPa prior to onset of melt, coinciding with a rapid increase in the Poisson’s ratio

Experimental geometry enabled very precise Hugoniot measurements at multi-Mbar stresses



- Sub-percent measurement of U_s and u_p
- Each point is a weighted average of 2 or 3 individual measurements (3 samples per panel)
- Significant benefit in being able to measure flyer plate velocity for impedance match

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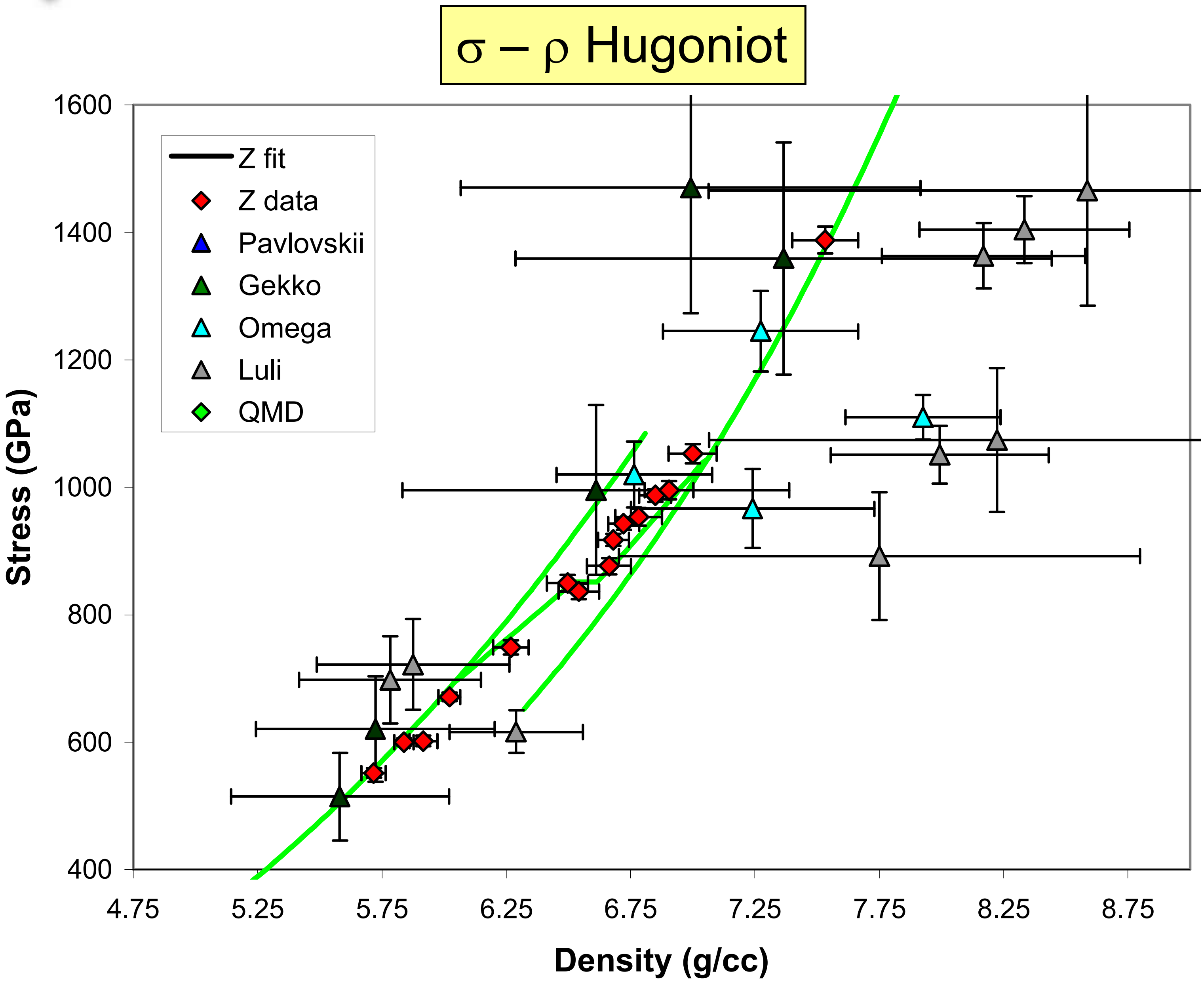
Experimental geometry enabled very precise Hugoniot measurements at multi-Mbar stresses



- Density precision of ~1% on average, as low as 0.67%
- High precision allows for quantitative comparison with theory
- These are by far the most accurate Hugoniot measurements of diamond in the multi-Mbar stress regime

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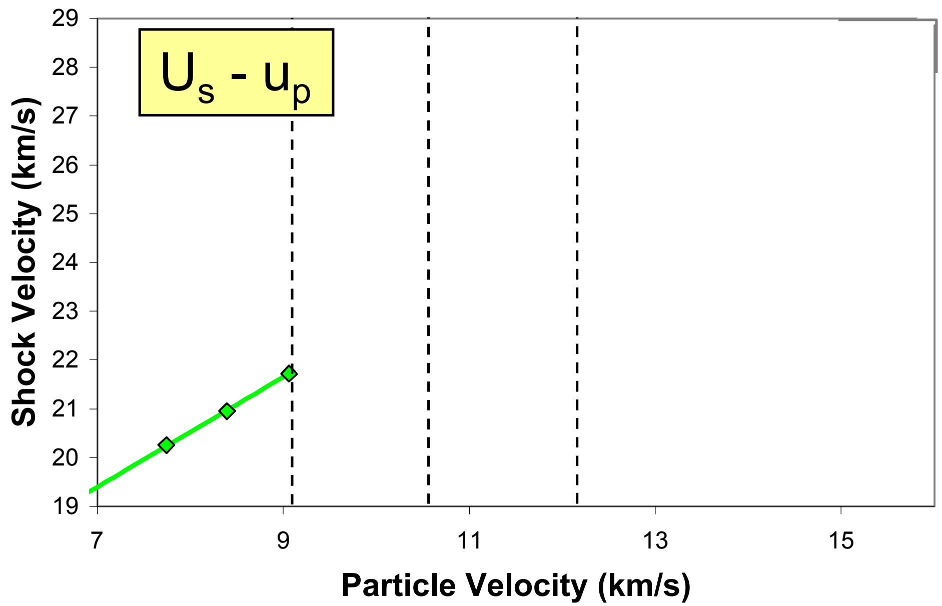
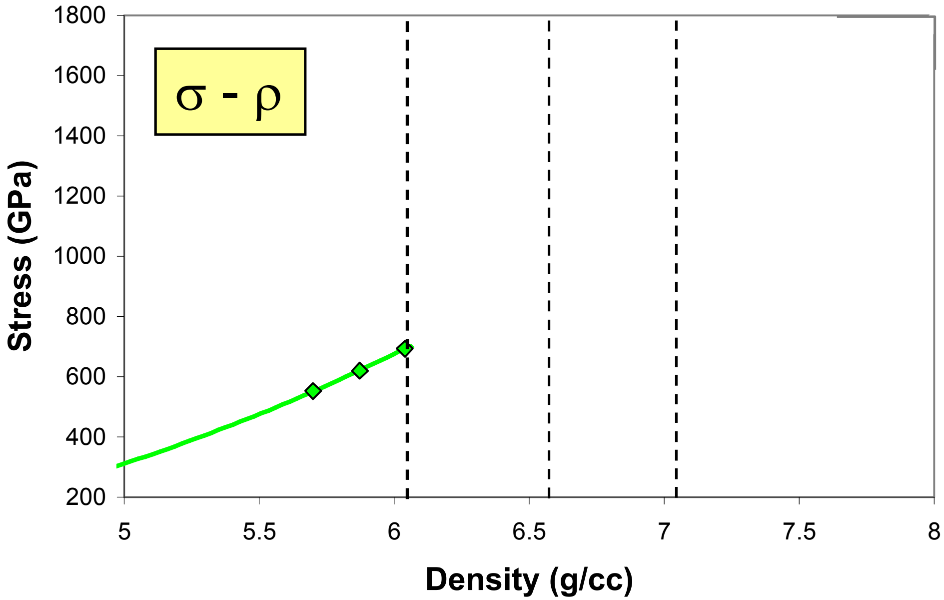
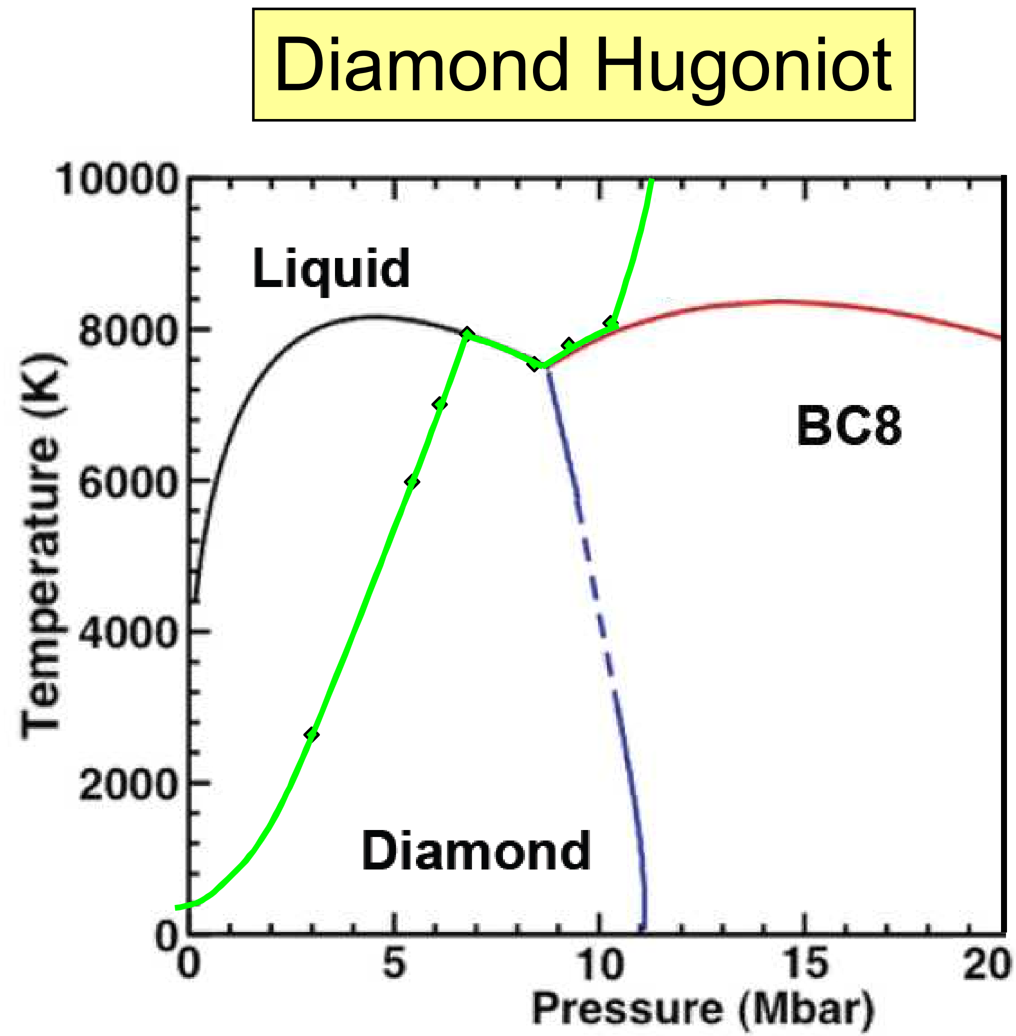
QMD calculations predict a diamond/liquid/bc8 triple point within the coexistence region

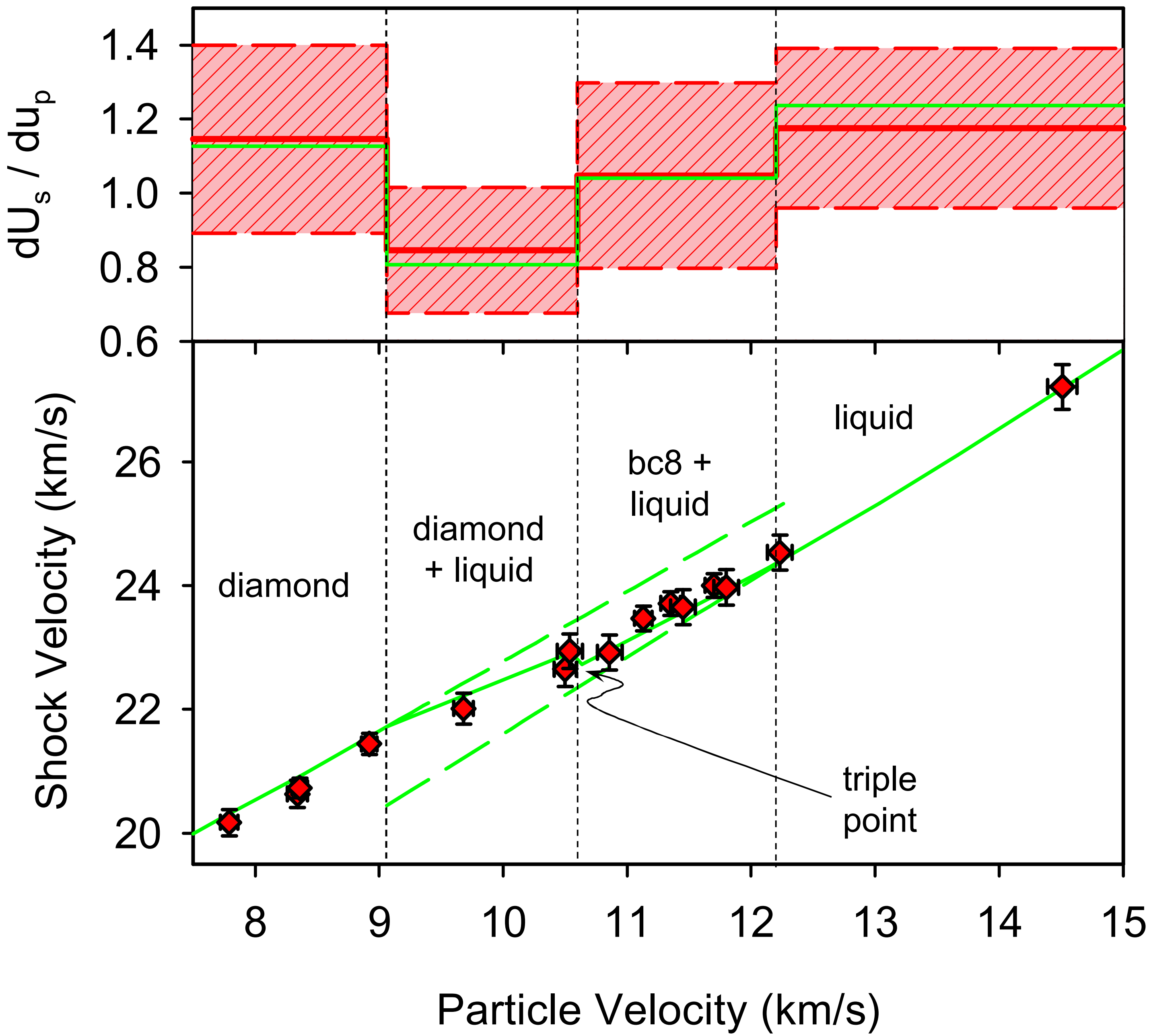






Correa, et al., PNAS **103**, 1204 (2006)

Z Hugoniot data is consistent with the trend in slopes predicted from the QMD calculations



- Piecewise weighted least squares linear fits to the Z data
- Linear segments determined from QMD predictions for onset of melt, triple point, and completion of melt
- Same trends in the magnitude of slope changes observed in experiment
- Experimental results consistent with QMD predictions regarding diamond-liquid-bc8 triple point

Diamond Conclusions

- Very precise Hugoniot data obtained for diamond between 550 and 1400 GPa
  - Consistent with QMD calculations which predict the onset of melt at ~690 GPa, a diamond-liquid-bc8 triple point at ~850 GPa, and completion of melt at ~1040 GPa
- Release data suggests significant yield strength in the shocked state below melt (~50-80 GPa)
  - Enabled trends in window transit time to determine onset of melt at ~650 GPa, in good agreement with QMD
- Impedance matching makes strong case for negligible shear stress in the shocked state, somewhat weaker case for initial release being hydrostatic
  - This issue could be addressed through reshock experiments on ZR