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UNR Grant Proposal Contribution

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The work of Carrier et. al. (citation needed for Matt’s effect of surface roughness on phase transitions/ETI paper) demonstrates that 1D and 2D resistive magnetohydrodynamic (MHD) simulations can reliably model exploding aluminum rods driven by megaampere currents. Close agreement between simulation results and photonic Doppler velocimetry data from the Mykonos electrothermal instability (METI-II) campaign builds confidence in predictive modelling capabilities for pulsed-power HED experiments. Furthermore, 2D MHD simulations show how machined features and micro-scale surface roughness can seed the electrothermal instability (ETI). Surface roughness was observed to reduce the time of melt by 19%, with ETI growth driving the enhanced heating of the rod surface.

A key finding from Carrier et. al. was the necessity for tracking the aluminum phases as illustrated by Figure 1 to determine where the exploding rod would be dense and reflective to the PDV laser. The “Cut-off” method in Figure 2 demonstrates that tracking the rapidly expanding liquid-vapor biphase material produces sudden accelerations/peaks in the velocity history.

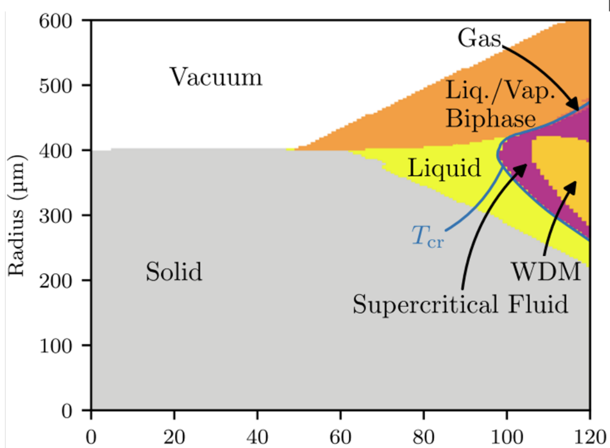

Figure 1. Phase tracking plot from 1D Lagrangian simulations done by Carrier et. al. The surface is observed to ablate at 48 ns prior to melt at 63 ns. The blue line represents the transition to supercritial fluid at the critical temperature.

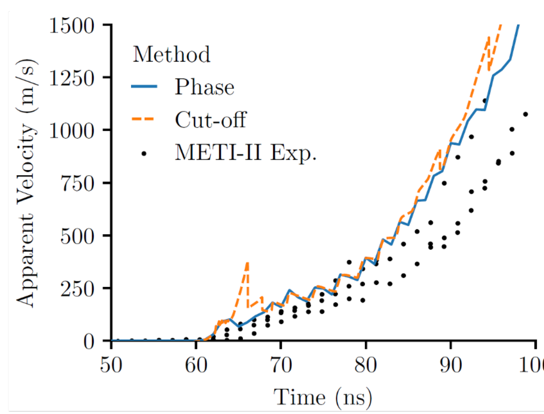

Figure 2. Apparent velocity plot from Carrier et. al., corresponding to the same simulation as Figure 1. The “cut-off” approach demonstrates spikes as low-density expanding material is tracked. Results are compared to experimental data from the METI-II experiments (black, circles).

This method neglects any computational zone where the electron density drops below the critical density of the PDV laser. Spurious peaks still develop with the cut-off method, as accelerating material that enters the thermodynamic region of liquid-vapor coexistence, or vapor dome, is tracked before expanding below the critical density. In comparison, the “Phase” method utilizes the pressure discontinuities at the edge of the Maxwell constructions of SES 93721 and the critical point to define the bounding saturation curves which define the vapor dome. Given that the early surface ablation seen in the simulations by Carrier et. al. are not observed experimentally, the rapidly expanding biphase material is to be non-physical. The Phase method enforces that any material that crosses into the vapor dome is ignored, therefore neglecting any liquid-vapor biphase material.

An ongoing effort of the past year has been an EOS sensitivity study of the 1D resistive MHD simulations of the Mykonos experiments. New higher resolution PDV data (citation needed for Aidan's paper) corresponding to exploding ultrapure (5N) aluminum rods motivated the comparison of simulations performed by Carrier et. al. to a repeated set of simulations, using 5N-Al (SES 93722) instead of Al-6061 (SES 93721). SES 93722 was not available in a Maxwell construction (MC) form, but rather only in a form exhibiting Van der Waals (VdW) loops. Prior to direct comparison of 6061 and 5N aluminum rod simulation results it became prudent to determine the impact of the choice of MC or VdW EOS.

The comparison given below by Figures 3-6 is the same simulation configuration as Carrier et. al., run with the MC (left) and VdW (right) forms of SES 93721.

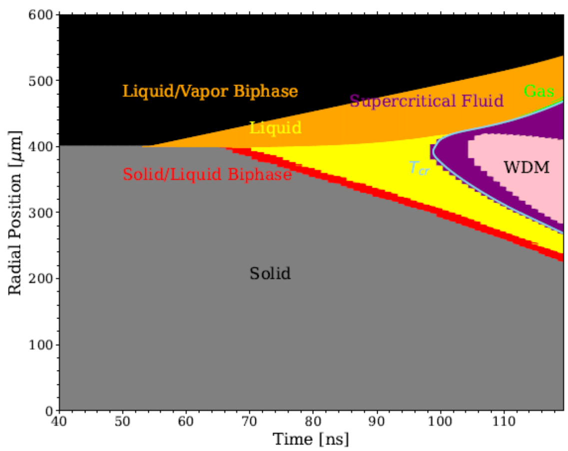

Figure 3. Phase tracking plot from 1D Lagrangian simulations using SES 93721 in MC form, with the same configuration as Carrier et. al.

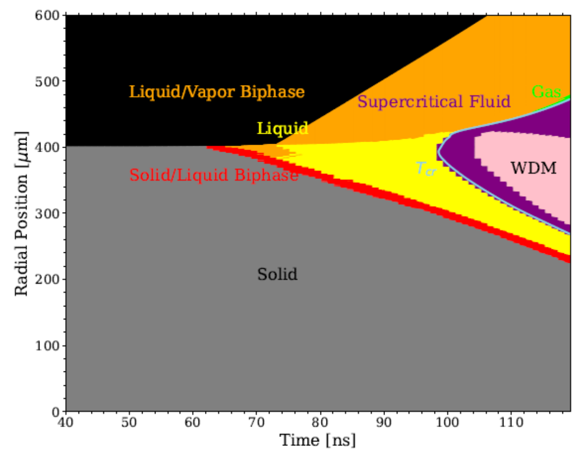

Figure 4. Phase tracking plot from 1D Lagrangian simulations using SES 93721 in VdW form, with the same configuration as Carrier et. al.

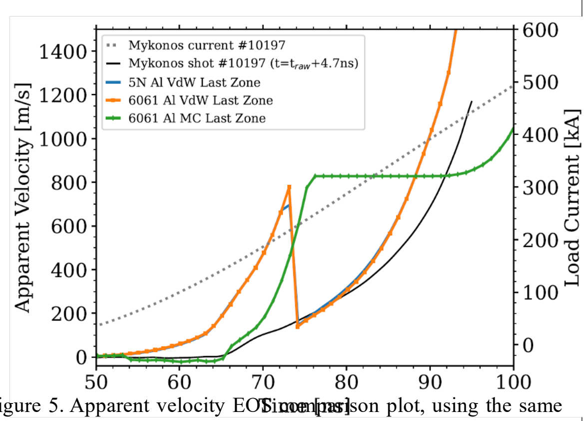

Figure 5. Apparent velocity EOS comparison plot, using the same simulation configuration as Carrier et. al. The velocity of the outermost aluminum zone is plotted without phase consideration.

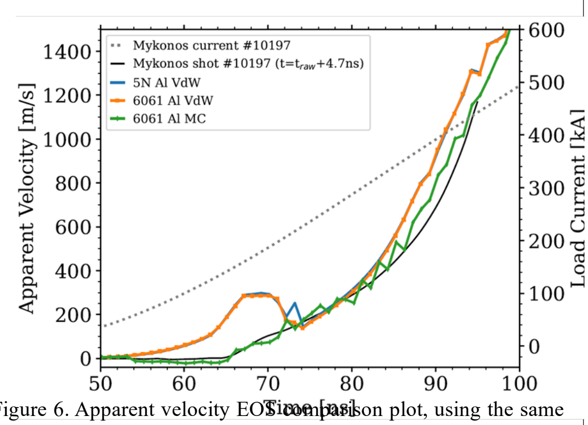

Figure 6. Apparent velocity EOS comparison plot, using the same simulation configuration as Carrier et. al. The velocity history utilizes the phase method to ignore liquid-vapor biphase material.

Analysis of simulations using either form of the aluminum EOS exhibit pre-melt ablation of the aluminum surface, however, the behavior of the VdW EOS surface prompted further investigation.

Unlike the MC simulation results, which show free isobaric expansion of material under the vapor dome, the VdW EOS results demonstrate that the pre-melt occurrence of biphase material can decompose once again into liquid phase. This difference in early-time behavior is highlighted by Figure 6, where aluminum zones "rebound" from the vapor dome between ~65-75 ns. (Needs times labelled)

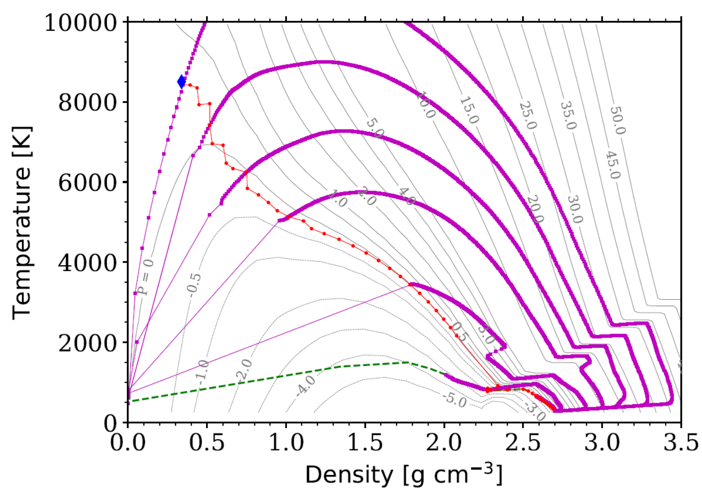

Figure 6. VdW EOS simulation results in (rho,T) phase space, superimposed (purple dotted lines) on SES 93721 isobars. The dashed green line follows the trajectory of the outermost aluminum surface zone, and the red dotted line tracks the closest non liquid-vapor biphase material to the outer surface as described by the phase tracking method.

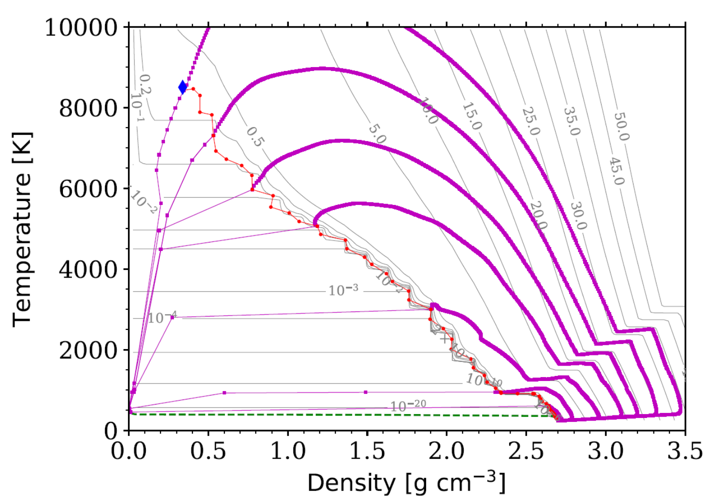

Figure 7. MC EOS simulation results in (rho,T) phase space, superimposed (purple dotted lines) on SES 93721 isobars. The dashed green line follows the trajectory of the outermost aluminum surface zone, and the red dotted line tracks the closest non liquid-vapor biphase material to the outer surface as described by the phase tracking method.

Although the spurious acceleration and phase tracking difficulties presented by Figures 3-6 would seem to suggest that VdW results are problematic and harder to interpret that the MC results, both exhibit similar problems at the vacuum interface.

The phase tracking method is more effective at providing accurate behavior of the aluminum interface for the MC EOS due to its pressure monotonicity, which prevents the phase “rebound” exhibited by the VDW results. Recent refinements to the simulation configuration have shown that resolution of the vacuum zone adjacent to the aluminum surface plays a more important

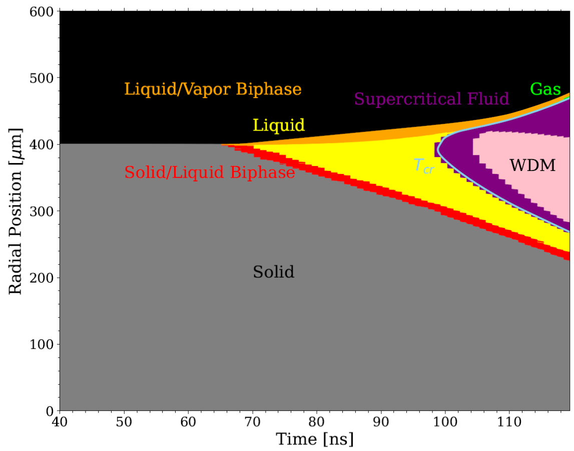

Figure 8. Phase tracking plot from 1D Lagrangian simulations using SES 93721 in MC form, with recently refined simulation configuration.

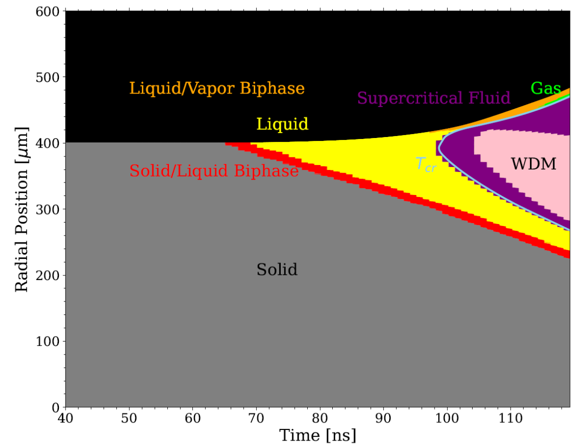

Figure 9. Phase tracking plot from 1D Lagrangian simulations using SES 93721 in VdW form, with recently refined simulation configuration.

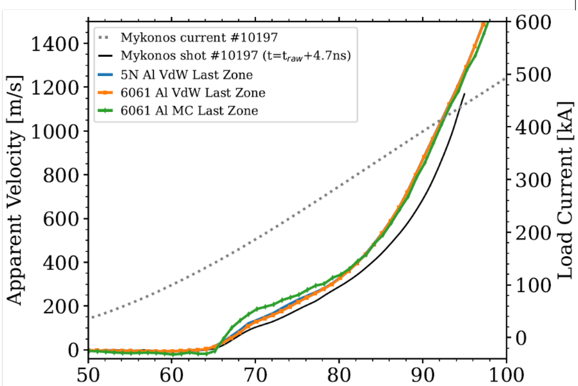

Figure 10. Apparent velocity EOS comparison plot, using the new simulation configuration. The velocity of the outermost aluminum zone is plotted without phase consideration.

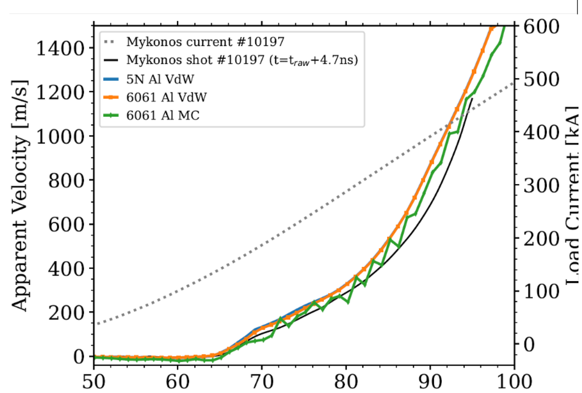

Figure 11. Apparent velocity EOS comparison plot, using the new simulation configuration. The velocity history utilizes the phase method to ignore liquid-vapor biphase material.

role in the expansion dynamics than previously considered. Refinement of the vacuum mesh near the rod surface prevents numerical issues upon simulation initialization and during melt which were found to induce earlier surface ablation than expected. Figures 8-11 illustrate how recent modifications have yielded results which are more consistent between MC and VdW simulations, and in better agreement with PDV data. A notable result shown by Figure 7 is that surface vaporization still occurs earlier in MC simulations relative to VdW simulations, but is now coincident with melt, as opposed to beforehand.

Recent 1D simulation results have shown far greater agreement between simulations using MC and VdW EOS forms, but further work is required to determine whether this consistency will extend to 2D or 3D simulations. Figures 11 and 12 show that significant differences between outer material behavior between VdW and MC results still exist in the new configuration.

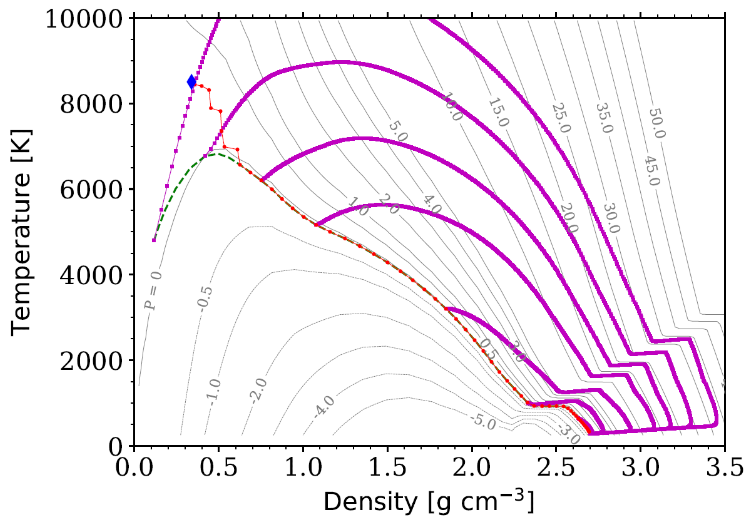

Figure 11. Current VdW EOS simulation results in (rho,T) phase space, superimposed (purple dotted lines) on SES 93721 isobars. The dashed green line follows the trajectory of the outermost aluminum surface zone, and the red dotted line tracks the closest non liquid-vapor biphase material to the outer surface as described by the phase tracking method.

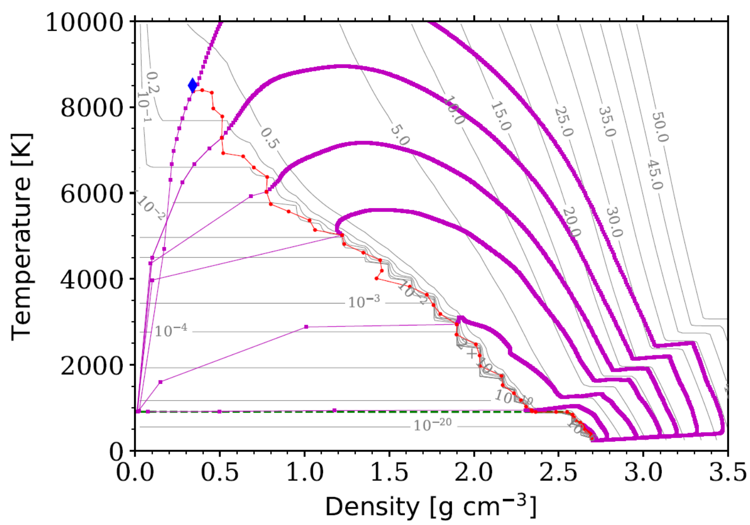

Figure 12. Current MC EOS simulation results in (rho,T) phase space, superimposed (purple dotted lines) on SES 93721 isobars. The dashed green line follows the trajectory of the outermost aluminum surface zone, and the red dotted line tracks the closest non liquid-vapor biphase material to the outer surface as described by the phase tracking method.

Higher dimensional simulations will provide insights on the EOS sensitivity of early-time ETI and transition to MRTI, as it is likely that differences in the surface behavior found in 1D results will become far more important.